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PROPERTY AND PRODUCTIVITY IMPROVEMENTS IN ELECTROSLAG AND ELECTROGAS WELDING

FINAL REPORT

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FOREWORD

The purpose of his report is to present the results of one of the research and development programs which was initiated by the members of the Ship Production Committee of The Society of Naval Architects and Marine Engineers and financed largely by government funds through a cost-sharing contract between the U.S. Maritime Administration and Bethlehem Steel Corporation. The effort of this project was directed to the development of improved methods and hardware applicable to shipyard welding in the U.S. shipyards.

Mr. W. C. Brayton, Bethlehem Steel Corporation, was the Program Manager; Mr. G. H. Reynolds of Materials Sciences Northwest, Inc. directed the development at Corvallis, Oregon.

Special acknowledgement is made to the members of Welding Panel SP-7 of the SNAME Ship Production Committee who served as technical advisors in the preparation of inquiries and evaluation of subcontract proposals.

EXECUTIVE SUMMARY

An apparatus has been developed for automated vertical welding in the electroslag and electrogas modes with addition of metal powder filler. Metal powder is dispensed in combination with shielding gas through a′ ceramic nozzle to the welding electrode where electromagnetic forces hold it in place and convey it to the weld pool. Welding tests using the new process have been performed on ABS Grades B and AH 36 plate. Both flux-cored and metal powder-cored electrodes were evaluated in the electroslag and electrogas modes. Solid electrodes were evaluated in the electroslag mode. Welding parameters found to be satisfactory for each mode of operation are presented. A detailed evaluation of weldment mechanical properties for procedures employing metal powder filler is presented. Preliminary results o the use of metal powder-bearing fluxes and ceramic backing tapes in electroslag welding with metal powder filler additions are presented.

Significant increases in welding process productivity have been realized through the use of metal powder filler in both the electroslag and electrogas processes. Productivity is found to increase in direct proportion to the amount of metal powder added. Mechanical property evaluations of welds produced in ABS Grade B plate with metal powder filler additions show the effect of such additions to be beneficial. Welds prodcued in ABS Grade AH 36 plate show mixed results in that a degradation of mechanical properties was observed in some welds when metal powder was added. Reductions in process heat input were observed in all welds as shown by reduced heat affected zone dimensions and grain size.

Both objectives of this project, increased productivity and improved weldment properties, have been met for most weldments produced with metal powder filler additions. The results of this investigation suggest that further study of metal powder additions to the electroslag and electrogas processes, particularly to the higher impat strength grades of hull steel, should be performed.

INTRODUCTION

This project had as its objective the development of equipment and welding procedures for the use of metal powder filler additions in both the electro-slag and electrogas processes. Metal powder filler additions were studied to improve the properties of electroslag and electrogas weldments by reducing process heat input and to improve the overall process productivity by increasing the total metal deposition rate. The project began with a review of world literature on metal powder filler additions to these processes. A computerized information retrieval search of the technical literature on electroslag and electrogas processes for the period 1966-1978 produced a total of 1615 entries. Of these, 621 were related to electrogas and electroslag welding. These were reviewed in detail for information relating to the use of powdered metal filler materials and mathematical modelling techniques in electroslag and electrogas welding. Manual review of literature published prior to 1966 and since 1978 was also performed. Three general reviews of the subject were found to be quite useful, those by Paton (l), Campbell (2) and Liby and Olsen (3).

Use of Powdered Metal Filler in Electroslag Welding-Process Considerations

The origin of the concept of using powdered metal filler in the electroslag welding process is clearly Russian although, as will be shown later, much earlier work on powder additions to the electroslag refining process was conducted in Western Europe and the U.S. First mention of the use of powdered metal in electroslag welding (references to work in progress) occurred in 1967 (4) and 1969 (5) and the first detailed description of weld metal micro-structure and mechanical properties appeared later in 1969 (6). This work

was an outgrowth of earlier work on metal powder additions to other forms of automatic welding, such as submerged arc and metal-inert-gas. An optimum powder/wire weight ratio of 1.05 was reported. Higher ratios led to lack of complete fusion of the powder. Welding speed was more than doubled and heat input almost cut in half. Tensile strength of welds made with powder was slightly lower than that of welds made without powder. Impact strength at +20°C was 30%, 110% and 14% higher for weld metal, fusion line and HAZ locations, respectively, for welds made with powder additions relative to those without powder additions. Considerably finer weld metal grain size was also noted when powder was used.

Equipment development, optimum powder sizes, energy consumption and process limitations were described in a 1972 paper by Ivochkin et al., (7). A 60% increase in process-thermal efficiency was reported-using a powder to wire weight ratio of 1.25. It was further reported that the powder electroslag process was used for welding the casing of a 3200 m^3 blast furnace at the Novolipetsk Steelworks in 1971 (7). Weld metal and HAZ grain refinement, and weld metal solidification structures were reviewed by Smirnov et al in 1973 (8). It was found that powder metal additions (and consequent travel speed increases) reduced the size of the columnar-grained zone of weld metal, decreased the cross-sectional diameter of such grains and improved the uniformity of mechanical properties across the weldment. The utility of powdered metals for making alloying additions was noted. Property improvements varied greatly according to the grade of steel tested.

A 1974 paper by Khakimov et al (9) disclosed the combination of powder

additions to electroslag welding with simultaneous trailing air-water spray cooling to control the overall thermal cycle of the weldment. Improvements in impact properties at temperatures as low as -60c were shown to result from combined powder additions and forced cooling.

Roshchupkin et al (10) reported the measured reduction of weld pool temperatures by 120C-150°C through the use of metal powder filler at approximately a 1:1 ratio. They concluded that metal powder additions were completely melted in the slag pool and could not act as weld metal solidification nuclei. They further presented an extensive discussion of the effect of powder additions on weld metal solidification mechanics and the origins of the disappearance of the typical columnar weld metal grain structure when welding with powders.

Eichorn and co-workers in Germany provided an important general confirmation of previous Russian results in 1976 (11,12), particularly with regard to reductions in process heat input and improvements in impact properties in both the as-welded and heat treated conditions. They examined weld metal microstructure by means of optical and electron microscopy (12). Further confirmation was recently provided in reports on two-wire processes using metal powder filler additions (13,14).

The use of grain refining and innoculant additions to electroslag welding such as titanium nitride (15) has been discussed and the use of ferrotitanium mixed with filler metal powder may be inferred from some of the Russian literature. Additions of titanium and boron in combination with filler metal powder were reported by Eichorn et al (13).

The addition of metal powder filler to other automatic arc welding processes such as submerged arc and metal-inert-gas has been the subject of numerous publications and is not included in this review.

Electrogas Process With Powdered Metal

The work of Eichorn et al (14) was the only reference reporting electrogas welding with metal powder filler additions.

Use of Powdered Metal Filler in Electroslag Refining

The use of powdered metal filler additions in-electroslag refining, completely analogous to electroslag welding, has had a considerably longer history. In 1948, Hopkins reported on what was then an “old” process for cladding (16) or electroslag casting (17) using powdered metal filler additions to produce the desired product chemistry. The Hopkins process metered controlled amounts of metal powders and ferroalloys into a continuously formed mild steel sheath to be consumed by process heat in either a submerged arc cladding operation or an electroslag casting operation. The metal powders were used to control the cladding or ingot chemistry. In more recent work, metal powder was fed onto a current-carrying electrode to be held in place by electromagnetic forces and conveyed into the molten slag pool in electroslag refining (18-24). It was claimed that up to a 4:1 weight ratio of metal powder to electrode wire (or strip) could be conveyed by electromagnetic forces (24).

Equipment Considerations

Equipment used for introduction of metal powder filler materials in electro-slag welding or refining may be divided into two types.

The first employs a large tubular electrode into which metal powders are continuously fed as in the Hopkins process (16,17). The use of large (ca. 30mm diameter) powder filled electrodes for electroslag hardfacing has also been reported (25).

The predominant method of introducing metal powder filler into the electroslag process has used the electromagnetic force field on the current-carrying electrode to hold filler metal powder in place (6-14). Metering devices for metal powder filler were described by Ivochkin (6,26). It was found that shielding of the powder dispensing device and use of non-magnetic materials in construction were particularly important in high-current welding operations. Eichorn (11,13,14) used a compressed gas (argon) to assure that the metal powder was conveyed onto the electrode-wire. Copper dispensing tubes are used with magnetic shielding provided to prevent the current in the electrode from causing the metal powder to bind in the tube (27). The utilization of the magnetic properties of powders and the electromagnetic force field around the current-carrying electrode has also been a feature of recent work on electroslag refining with powdered metals (18-24).

Mathematical Modelling of the Electroslag Welding Process With Powder Additions

Roshchupkin et al (10) have presented relationships for dendrite width in relation to process parameters and solidification velocities and discussed the effect of powder additions on these relationships. Numerous general attempts at mathematical modelling of the weld metal and HAZ thermal history have been presented, only a few of which will be discussed here as they relate to metal powder additions. The early treatments by Eregin (28,29)

permit some generalized predictions of the effect of metal powder additions. The increase in welding speed and the reduction in penetration possible through-the use of supplemental filler metal would have a very significant effect on reduction of the extent of the HAZ and grain size therein. Reducing the joint gap width has a similar effect. Actual effects of metal powder additions on weld pool temperatures, slag temperatures, and slag conductivity on the predictions of the models are expected to be quite complex, however. No comprehensive model including all of these factors has been presented in the literature.

EQUIPMENT DEVELOPMENT

The experimental equipment used in this project was designed and constructed to facilitate the addition of metal powder filler to the electroslag and electrogas processes and to provide the maximum flexibility-in adjustment of operating parameters. The equipment permitted a maximum weld length of 24.0 in. in plate up to 3.0 in. thick with a single, oscillated electrode.

Figure 1 shows an overall view of the experimental welding apparatus. From left to right in this figure are the welding head, control console with walk-around control box and the 1200A power supply. The control console contains potentiometers for control of the metal powder and flux metering systems and for vertical travel. speed, wire feed and oscillation frequency. Off-on controls for all necessary functions are provided on the walk-around box. Figure 2 shows the welding head assembly with wire reel, straightener, wire feeder and nozzle. Figure 3 shows the wire straightener and Lincoln wire feeder used. In the lower left of the figure is the sine wave crank-type

oscillator which drives the entire welding head on its slide. The welding head detaches from the vertical slide immediately behind the wire feed motor permitting attachment to a tractor or crawler.

A front view of the welding head with metal powder and flux dispensing tubes in place is shown in Figure 4. Metal powder is dispensed below the contact tip and flux dispensed above the nozzle, although, in principle, they can be dispensed together below the contact tip. This view shows the original metal dispensing tube which was later replaced with a ceramic nozzle. The front of the metal powder and flux metering devices are also shown. Figure 5 shows the Tapco metal powder and flux metering devices. The metal powder metering device is equipped with a shielding gas line so that shielding gas (Ar-25% CO_2) may be used to assist in conveying the metal powder to the electrode during welding.

Figure 6 shows two views of the pneumatically activated, moving water-cooled copper shoe. The length of the travelling shoe is 4.5 in. During welding, this traveling shoe is held in place against the plate surface by 25 p.s.i. air pressure. A water interlock is provided so that loss of water pressure during welding disengages the power supply. The final configuration ceramic nozzle used for dispensing metal powder is also shown in this figure. Prior to each welding test, the nozzle was coated with an antispatter compound. The pattern of metal powder dispensing from the ceramic nozzle with a shielding gas flow of 12 cfh. is shown in Figure 7. The powder contacts the electrode approximately 0.5-0.75 in. below the contact tip during welding. During welding, the powder is held in place where it contacts the electrode rather

than free falling as shown in the figure.

Figure 8 shows two views of the welding head in position for the start of welding on the run-on tab. A 17.0 in. stationary water-cooled copper shoe is used. For some welding tests conducted during this project, the stationary water-cooled copper shoe was replaced by refractory ceramic tile backing tape. Midpoint of electroslag welding a 15.0 in. long plate is shown in Figure 9 while the finish of the plate is shown in Figure 10. Note that no run-off tabs are used. In no case was any cracking of the bead at the finish of the weld observed even under the most severe strongback restraint conditions. A completed electroslag weld before slag removal is shown in Figure 11.

WELDING TESTS

General Considerations

Two types of metal powder filler were examined at the beginning of the project. These were Hoeganaes Type 434 iron powder and Hobart Type 525 alloy steel powder. The Hoeganaes 434 is the principal ingredient-in blended powder compositions commonly used for submerged arc welding. This powder has a somewhat lower packing density than the Hobart 525 powder. As a consequence, the Hoeganaes 434 powder does not "pack" as well on the electrode when held in place by electromagnetic forces and is more easily stripped from the surface of the electrode by the molten slag when operating in the electroslag mode. The more spherical Hobart 525 powder was found to pack more densely on the electrode as is therefore better conveyed through the molten slag and into the weld pool. Also, the lower surface area of the Hobart 525 powder seems to be an aid to complete powder consumption during welding and minimization of the tendency for a fraction of the powder to float on the surface of the slag. For these reasons, all welding tests described in this report utilized the Hobart 525 powder except where other-wise noted.

The concept of electromagnetic feeding of metal powder to the weld works progressively better as welding current is increased, i.e. as the magnetic field strength around the electrode is increased. At low currents, the metal powder may be attracted to the walls of the test plate or stripped from the electrode and remain on the surface of the molten slag. At higher current levels, this tendency decreases and a larger fraction of powder is held on the surface of the electrode and conveyed through the slag. At welding currents typical of the tests performed in this project (ca. 500-700A),

virtually all the metal powder is bound to the electrode and conveyed into the weld pool. This is particularly true in the electrogas mode of operation.

Welding voltage is found to be the most significant variable when electroslag or electrogas welding with metal powder filler additions. Higher welding heat inputs associated with higher voltages also tend to produce a hotter and more fluid slag which assists in the introduction of metal powder into the weld pool. Welding with metal powder filler additions therefore requires an increase in operating voltage, for the reason just cited, to avoid lack of fusion defects resulting from the cooling effect of the metal powder. Such welding voltage increases are typically 10-20% over baseline (no powder) conditions.

Following removal of the slag by chipping and light sandblasting, each welded test plate was x-rayed and ultrasonically scanned for the presence of defects in the as-welded condition. Following non-destructive examination, the plates were subjected to tensile, bend and impact testing (Charpy V-notch) at a temperate appropriate to the particular ABS grade of plate being tested. Impact specimen locations were at weld metal centerline, in the heat affected zone 3.0 mm from the fusion line and in the base metal. Tests were conducted near the mid-length of the welded plate, i.e. approximately 8.0 in. from the start of the weld for plates 15.0 in. long. Brinell hardness was determined directly for weld metal, heat affected zone and base metal locations on transverse sections. Metallographic specimens were prepared from both longitudinal and transverse sections showing the weld metal

structure and the full extent of the heat affected zone. These specimens were polished, etched and photographed for record. Hardness traverses (Rockwell “B”) were made at 2.0 mm intervals from the weld metal centerline through the heat affected zone and into the base metal. Heat affected zone widths at the mid-plane of the plate were measured on the transverse sections.

Electroslag Welding Tests (0.50 in. Root Opening)

Table I shows the parameters which were held constant for all welding tests unless otherwise noted. Tables which follow show welding parameters which were varied for each of the electrodes tested. In all of these tables, the parameters presented are those which were found to produce satisfactory welds with acceptable soundness and the absence of lack of fusion defects, flux entrapment or incomplete metal powder fusion. Data from welding tests which did not produce satisfactory results are presented later on in this report as part of a general discussion of the effect of metal powder filler additions on process heat input.

Flux-Cored Electrodes

Hobart Fabco 81

Linde 124 was used as a starting flux to establish the conductive slag layer. Further additions of flux were not required during welding since the flux content of the electrode was sufficient to maintain the electroslag operation.

Table II shows welding parameters both with and without metal powder filler additions on ABS Grade B plate. The deposition rate for the electrode was increased from 33.75 lbs/hr. with no powder addition to as high as 67.5 lbs/hr. at a powder

to electrode ratio of 1.0. (Metal deposition rates for flux-cored electrodes are not corrected for flux weight and may be assumed to be approximately 10% high.) This increased deposition rate is accompanied by a decrease in process heat input. The decrease in process heat input is less than that expected from the increased travel speed because voltage must be increased when metal powder is added. Table II illustrates very dramatically the significant increase in process productivity possible through the use of metal powder filler additions. The Hobart Fabco 81 electrode was found to be ideal for purposes of experimentation with the process because of the stable behavior in the electroslag mode and the absence of the need for continuous flux additions.

Table III shows the mechanical properties of the three test plates prepared with the Hobart electrode. Tensile strength was acceptable for all three plates. A significant increase in both weld metal and heat affected zone impact strength is found through the addition of metal powder filler at a 0.50 ratio. Average weld metal impact strength is increased from 21.0 to 35.8 ft-lbs. , while average heat affected zone impact strength is increased from 89.3 to 107.7 ft-lbs. Specimens taken from the plate welded at a 0.85 ratio show a decrease in both weld metal and heat affected zone impact strength although properties are equivalent to those of the plate welded without metal powder. As Table II shows, however, the increase in productivity relative to the plate welded without powder is very significant.
It is interesting to note that the heat affected zone impact strengths of all three electroslag welded plates are significantly higher than the base metal average of 69.3 ft-lbs. The mechanical property data obtained in these

tests suggest that the 0.85 ratio may be somewhat above the optimum as far as mechanical properties are concerned.

Metallographic specimens prepared from the three plates are shown in Figures 12-14. A reduction in the extent of the heat affected zone resulting from the addition of metal powder filler is apparent. This is expected from the reduced heat inputs shown in Table II. The photomicrographs of the three weldments in Figures 12-14 show that the degree of grain coarsening within the heat affected zone appears to be less for the plates welded with metal powder filler. It may also be noted in these figures that the amount of penetration of the baseplate, i.e. the actual width of the weld, decreases with increasing amounts of metal powder filler. Finally, weld metal grain size, particularly the coarse columnar grains adjacent to the fusion line, appears to be progressively smaller with the addition of metal powder filler. Results of the hardness traverses across the transverse sections are shown in Figure 15. Heat affected zone widths are tabulated and shown graphically in a later figure in this report. These results will be presented, in comparison with the other electrodes, in the Discussion section.

McKay Speedalloy 75

This electrode could not be made to operate in the electroslag mode in combination with the Linde 124 flux. Excessive amounts of flux addition were required to keep the arc submerged. The slag was very active with considerable spatter which plugged the ceramic powder dispensing nozzle. In the operating range 26-40 V, 300-600 A with metal powder ratios of 0-0.4, no satisfactory welds were obtained. Lack of fusion defects were

sent in each weld.

Hobart PS 588

Table IV shows operating parameters which produced satisfactory weldments using this flux-cored electrode with the Linde 124 flux. As shown in this table, welds were produced with powder to electrode ratios as high as 1.0 corresponding to a total metal deposition rate of 67.5 lbs/hr. at a process heat input of 270,000 J/in.

When these tests were repeated after a time interval of approximately three weeks, satisfactory welds were produced but the electrode/flux combination produced a more active slag than was present in the first tests even when the flux was thoroughly dried before using. On this basis, it is possible that moisture pick-up over time may be a problem with this electrode.

Airco Supercore

Excellent performance, similar to the Hobart Fabco 81, was observed. Continuous addition of Linde 124 flux was required during operation, however, to keep the process fully submerged. Table V shows welding parameters found satisfactory for use with metal powder filler additions. Total metal deposition rates were slightly lower than those obtained with the Hobart Fabco 81. This electrode was tested at powder to electrode weight ratios as high as 1.13 which produced some unmelted powder on the

Optimum metal

powder ratio is felt to be in the range 0.5-0.8.

Electrogas Welding Tests (0.50 in. Root Opening)

Satisfactory electrogas welds were made using the Hobart PS 588 and Airco Supercore electrodes. Only a small number of tests were conducted with these two electrodes and welding parameters will not be discussed here. The major portion of the electrogas welding tests with 0.50 in. root openings were performed with the Lincoln 431 Innershield electrode.

Lincoln 431 Innershield

Table VI shows welding parameters which were found satisfactory for this electrode. Consistent with manufacturer's recommendations, the electrode performed best at relatively high operating voltages. Significant productivity increases were observed to result from metal powder filler additions accompanied by a decrease in process heat input. Appearance of the completed welds was considered the best in general of any electrode tested. Mechanical properties and weld metal microstructure were evaluated on narrow gap (0.375 in. Root Opening) welds made with this electrode which will be discussed in a following section.

Narrow-Gap Electroslag Welding Tests (0.375 in. Root Opening)

In an attempt to further reduce process heat input when welding with metal powder, the welding head was modified to permit narrower root openings and consequent higher travel speeds. The welding nozzle was modified to increase the angle between the welding electrode and and the vertical direction from the original 10° shown in Table I thereby permitting the use of narrower gaps when welding with the metal powder filler additions. The modified nozzle provided an angle of approximately 30° from the vertical reducing

the root opening to 0.25 in. During operation, it was found that this electrode angle was too large since very slight variations in the level of the slag during welding permitted large changes in the horizontal displacement of the electrode and led to severe arc strikes on the stationary copper shoe. For this reason, the electrode angle was decreased to approximately 20° permitting a minimum root gap of 0.375 in. This configuration proved satisfactory and was retained. The “narrow gap” welding tests retained all of the operating parameters shown in Table I with the exception of increasing the electrode angle to 20° and decreasing the root opening to 0.375 in.

Metal Powder-Cored Electrodes

McKay 215463-ES

This electrode contains a metal powder core which constitutes approximately 40% of the weight of the composite electrode. Table VII shows welding parameters found satisfactory for use with this electrode in combination with Arcos BV flux on Grade AH 36 plate. As shown in this table, welds were produced with powder to electrode ratios as high as 0.5 corresponding to a total metal deposition rate of 50.63 lbs/hr. at a process heat input of 315,000 J/in. Welding tests performed at ratios higher than 0.5 were unsuccessful in that the welds were consistently cold, i.e. the additions of flux during welding resulted in lack of fusion defects at each point where the flux was added. The high metal powder content of the core itself may produce significant cooling of the weld pool. Addition of a small amount of metal powder filler therefore leads very quickly to a “cold weld” situation.

With the McKay 215463-ES/Arcos BV combination, the weld surface was

consistently “pock-marked” on the side of the stationary water cooled copper shoe. The “pock-marked" appearance was not observed in any other wire/flux combination studied and appeared to be independent of any process parameters. The pock-marked surface of the weld appeared to have no effect on weld metal soundness.

The plate welded with wire only showed acceptable soundness in radiographic and ultrasonic examination while the plate welded at a powder to wire ratio of 0.5 contained elongated porosity throughout the length of the weld. Mechanical properties measured for the McKay 215463-ES/Arcos BV combination are shown in Table VIII. The yield strength of the weld made with metal powder addition was slightly higher than that made with no powder while the ultimate tensile strengths are identical. Weld metal Brinell hardness was higher for the weld made with no powder.

Table VIII shows the CVN impact strength at -4°F for these weldments. The weld metal impact strength is slightly lower for the sample welded with metal powder additions while the HAZ impact strengths are slightly higher. Both sets of HAZ impact strengths would be considered unacceptably low. The base metal impact strength is also quite low. As noted in the non-destructive examination of these weldments, the weld metal produced with metal powder filler additions contained a considerable amount of elongated porosity. The influence of this porosity of the impact strength remains problematic.

Figures 16 and 17 show metallographic cross-sections of both weldments.

Weld metal grain size and degree of HAZ grain coarsening are essentially identical for both plates. The porosity in the plate welded with metal powder additions is apparent in Figure 17. The hardness traverse of each weld is shown in Figure 18. Weld metal and HAZ hardness were significantly lower when metal powder was added although the hardness at the fusion line was increased slightly.

Linde MC 70

This metal powder-cored electrode was tested in combination with Linde 124flux. at metal powder ratios of 0.47 and 0.85 on Grade AH 36 plate. It was found useful to increase electrode extension by 0.5-1.0 in. beyond that shown in Table I when welding with this electrode. Other welding parameters which were found satisfactory for this wire/fluxx combination are shown in Table IX while the mechanical properties of the resulting,weldments are shown in Table X. Yield and tensile-strengths were essentially identical for plates welded with or without metal powder additions. Weld metal impact strength increased with increasing amounts of metal powder while HAZ impact strength decreased when metal powder was added. HAZ impact strength of the two plates welded with metal powder additions were slightly higher than base metal values for the AH 36 plate.

Photomicrographs of the weld metal structures are shown in Figures 19-21 while the results of the hardness traverses are shown in Figure 22. Weld metal, fusion line and HAZ hardness were all lower when metal powder was added.

Solid Electrodes

Linde 29S

This electrode was tested in combination with Linde 124 flux at metal powder ratios of 0.54 and 0.98 on Grade AH 36 plate. Table XI shows the welding parameters found satisfactory for use with this electrode/flux combination. Weldment mechanical properties are shown in Table XII. Yield and tensile strengths were essentially identical for plates welded with or without metal powder additions. Weld metal impact strength decreased with the addition of metal powder at a ratio of 0.54 and increased to the level of the plate welded without metal powder when.a ratio of 0.98 was used. The highest HAZ impact strengths were observed for the plate welded with metal powder at a 0.54 ratio. The low base metal impact strength is also to be noted.

Figures 23-25 show the metallographic cross sections of the three plates welded with the Linde 29S electrode and Figure 26 shows the results of the hardness traverses. The hardness in the weld metal, fusion line and HAZ was lowest for the plate welded at a ratio of 0.98. Unusual fluctuations in the hardness curves for the plate welded with no metal powder are seen in the vicinity of the fusion line.

Narrow-Gap Electrogas Welding Tests (0.375 in Root Opening)

Lincoln 431

Table XIII shows the welding parameters found satisfactory for use with this electrode on Grade AH 36 plate. Welding tests were conducted at powder/wire ratios of O and at 0.5 using two different powders. These two powder types were. Hobart 525

a special atomized powder, Tapco High Al, having a chemistry reasonably close to that of the Lincoln 431 weld metal deposit.* In Table XIII, welding process parameters at a ratio of 0.8 are also included.

Welding performance of this electrode was considered exceptionally good. Finished bead appearance was the best of any electrode, either electroslag or electrogas, tested in these experiments. All plates welded with the Lincoln 431 Innershield electrode with and without metal powder filler additions showed acceptable soundness in radiographic and ultrasonic examinations.

Table XIV shows weld metal yield and tensile strengths observed for these plates. Yield and tensile strengths for all three welds are virtually identical. Significant differences were observed in impact strengths. Weld metal impact strength at -4°? was considerably lower for the plates welded with metal powder filler additions than that welded with wire only as are HAZ impact strengths. Comparing the two types of metal powder filler additions, inferior properties are obtained with the High Al powder relative to those obtained with the Hobart 525 with the former having impact strengths at an unacceptably low level.

Figures 27-29 show the microstructure of the electrogas welded plates. No significant difference in weld metal grain size is observed for the

*High Al Powder Chemistry (Wt.%): Al 0.31, C 0.038, Co 0.01, Cr 0.18, Cu 0.07, Mn 1.21, Mo 0.028, Ni 0.07, Si 0.27, V 0.019, Fe Bal.

three plates. Figure 30 shows the results of the hardness traverses across the three welds. The plate welded with the Hobart 525 powder at a ratio of 0.5 shows the lowest weld metal, fusion line and HAZ hardness while the hardness curves for the weld made with no metal powder and with the High Al powder are very similar.

Airco Metal Core 6

Table XV shows the welding parameters found satisfactory for use with this electrode with no metal powder and with a ratio of 0.5 on ABS Grade B plate. In practice, it was found that a slightly rough bead surface was obtained when shielding gas only was used. This surface roughness could be eliminated by the addition of very small amounts of flux during welding.

The 0.50 ratio test plate prepared for mechanical property evaluations was found to contain gross centerline porosity. There is reason to believe that this porosity was the result of moisture pick-up in the metal powder. This plate was nonetheless subjected to testing so that impact properties could be determined. Table XVI shows the results of the mechanical properties tests. The low tensile strength and elongation of the plate welded with metal powder are due to the porosity in the weld metal centerline region. Highest weld metal impact strength was found for the plate welded with metal powder while the reverse was true for HAZ impact strength.

Figures 31 and 32 show the metallographic cross sections of these welds. Figure 33 shows the results of the hardness traverses. Weld metal hardness was higher for the plate welded with metal powder while the plate welded without powder showed the highest HAZ hardness.

Narrow-Gap Electroslag Welding Tests (23.0 in. Long Plate)

In an attempt to determine whether the welding process had stabilized and could be expected to yield uniform weldment properties over the entire length of weld, the water-cooled stationary shoe was extended to permit welding of 23.0 in. long plates. The Hobart Fabco 81 electrode was used with no flux additions other than Linde 124 as a starting flux. Table XVII shows the welding parameters used to produce a heat input of 216,000 J/in. at a metal powder ratio of 0.5. The weld was found to be sound in both radiographic and ultrasonic inspection.

The plate was tested at locations 8.0 and 18.0 in. from the start of the weld. The results of these tests are shown in Table XVIII. Tensile properties at the 8.0 and 18.0 in. locations are identical. Impact strengths are quite similar at the two locations with the 18.0 in. location showing slightly lower values for both weld metal and HAZ. Preparation of welds of much greater length, at least several feet, would be necessary to determine whether the metal powder process has reached steady-state operation and will. not produce any degradation of weldment mechanical properties. The results of this test suggest that such a degradation is not expected.

Additional Electroslag Welding Tests

Several experiments were conducted using an Airco constant Potential Power supply for examination of the performance of the experimental apparatus with a CP supply. These tests were conducted using the Hobart Fabco 81 flux-cored electrode.

The tests showed the welding behavior of the experimental apparatus both with and without metal powder filler additions to be satisfactory with the CP supply.

Metal Powder-Bearing Fluxes

Linde 39B and Airco (Kobe) metal powder-bearing fluxes were evaluated with and without metal powder filler additions. Although these fluxes were not originally devised for electroslag welding, both appear to show considerable promise for this type of usage. With both fluxes, the process could not be started using the metal powder-bearing flux since they tended to bridge over rather than fuse and explode. from the weld. For this reason, Linde 124 was used as a starting flux to initiate the conductive slag layer. Gradual additions of the metal powder-bearing flux were made during welding until the slag consisted of 100% metal powder-bearing flux.

Linde 39B

Table XIX shows welding parameters found satisfactory for this flux used in combination with the Airco Supercore flux-cored electrode both with and without metal powder filler additions. When adding flux during operation, the flux is magnetically attracted and adheres to the walls of the base plates because of the metal powder contained within the flux. This served to “precoat” the plate walls with flux and was not found to be objectionable. Satisfactory welds were also produced using the metal powder metering device to dispense the 39B flux which was weakly bound to the electrode and carried to the slag pool during welding.

This flux was found to be voltage sensitive during operation. At high operating voltages (38-40V), there was a strong tendency for stray arcing through the unmelted flux which adhered to the walls of the plates. At lower operating voltages (28-34V), the behavior,of this flux in electroslag operation was quite satisfactory. Weld appearance and soundness were satisfactory and-no tendency for weld metal cracking was observed. Flux peeling characteristics were acceptable.

Airco (Kobe) Flux

Electroslag welding with this flux was somewhat more erratic than with Linde 39B. Table XX shows welding conditions found satisfactory with and without metal powder filler additions. The high voltage required for complete. consumption of metal powder filler additions tended to make the process unstable with an arc pulsating in and out of the molten slag layer. The flux is stable at lower voltages in electroslag welding but quite sensitive to changes in operating variables. The same tendency for flux adherence to the walls of the test plate and arcing through the bound flux at high voltages was also noted. Peeling characteristics of the flux were very good but the shape of the finished bead tended to be somewhat irregular at all operating voltages.

Electroslag and Electrogas Welding With Ceramic Backing Tape

Two types of ceramic tile backing tape produced by 3M were evaluated for the purpose of replacing the stationary copper shoe. It was felt that the reduced heat input possible with electromagnetic feeding of high ratios of metal powder would permit the use of the ceramic backing. (It is acknowledged

the 0.5 in. root opening used was probably too large. The likelihood of success would be significantly improved by a reduction in the root gap.)

The 4.5 in. moving shoe used for most of the welding tests was replaced by a 6.0 in. moving shoe to provide additional cooling power. Successful electroslag and electrogas welds were made at a powder to electrode ratio of 1.0 and a travel speed of approximately 5.0 ipm: only a small percentage of the welds attempted, however, were successfully completed. The principal difficulty encountered with the ceramic tile backing tape was in starting the process. Since only one cooling shoe was used, runouts could occur before the process could be stabilized and powder addition begun. During operation, runouts were observed to be due not to any failure of the ceramic tile but to failure to contain the molten metal between the edge of the tile and the base plate. This resulted from the ceramic tile not being sufficiently tight against the base plate.

Both the electroslag and electrogas welding with ceramic backing tapes and metal powder filler additions should be feasible particularly if narrower root openings are used. In the present work, the 0.50 in. root opening meant that occasionally the width of the weld bead became greater than the width of the ceramic tiles.

DISCUSSION OF RESULTS ON ELECTROSLAG AND ELECTROGAS WELDING TESTS

Since the two major objectives of this program are improved productivity and improved weldment properties through decreased process heat input, it is interesting to group all the welding test results in a master plot of

metal powder versus process heat input. Data for all electroslag and electrogas electrodes are shown in Figure 34 and, even with the considerable diversity of electrode types and welding conditions, a surprisingly coherent picture emerges. In this figure, the filled points represent satisfactory performance, i.e. sound weld metal, free of lack of fusion defects. The open points represent insufficient process heat input which results in lack of fusion defects, unmelted powder in the weld and/or slag entrapment. Figure 34 pertains to the 0.50 in. root opening/ 25° included angle joint geometry and 3/32 (.094) in. electrode diameter.

Examination of the figure shows a trend in the data despite the diverse types of electrodes used. At a metal powder ratio of O, satisfactory electroslag or electrogas welds can be produced at process heat inputs in excess of approximately 325,000 J/in., while at lower process heat inputs unsatisfactory welds are produced. As the metal powder to electrode ratio is increased to 0.5, satisfactory welds can be produced at process heat inputs in excess of approximately 275,000 J/in., while at lower inputs, unsatisfactory welds are obtained. This means that as metal powder is added to the weld, the powder is actually being consumed by excess process heat, i.e. the process is becoming more “efficient” as well as more productive. With further increases in the metal powder ratio to approximately 0.75, sound welds may be produced at lower heat inputs of 240,000 J/in. However, as the metal powder ratio is further increased to the vicinity of 1.0, the process heat input must be increased to avoid lack of fusion defects in the weld. From the standpoint of efficiency, the optimum ratio of metal powder to electrode has been exceeded. Productivity continues to increase as long as a satisfactory weld can be produced.

An approximate dividing line between sound and unsound weldments when metal powder ratio is plotted against process heat input thus exists. Sound welds are produced to the right of the dividing line and lack of fusion defects are encountered to the left.

Figure 35 shows the corresponding data points for the narrow gap (0.375 in. root opening, 25° included angle) welding tests. Examination of this figure shows the same general trend in the data as discussed above. It was originally expected that the dividing line between sound and unsound weldments would be shifted to the left for the smaller root opening which was not observed. This was due to the fact that higher voltage and current settings, particularly voltage, were found necessary to produce sound welds in the narrow gap joint configurations. These higher input power settings offset the heat input reduction due to the-higher travel speeds possible with the narrow gap. As examples, compare Tables II and XVII for a metal powder ratio of 0.5 for the Hobart Fabco 81 electrode and Tables VI and XIII at a ratio of 0.5 for the Lincoln 431 innershield electrode.

The results of the measurements of HAZ widths at the mid-plane of the test plates are given in Table XXI and shown graphically in Figure 36 for electroslag welds. This data shows quite dramatically the decreased process heat input possible with metal powder additions to the electroslag welding process. HAZ widths for the electrogas weldments are given in Table XXII and shown graphically in Figure 37. These data confirm the lower process heat inputs afforded by metal powder additions to the electrogas process. As shown in each of the welding procedures developed in this project, this reduced process

heat input is accompanied by an increase in overall process productivity, as measured in total pounds per hour of deposited metal, which is directly proportional to the amount of metal powder added.

The studies of Smirnov et al (8) showed that the degree of weldment property improvement varied markedly with the grade of steel tested when metal powder filler was added. In testing plain carbon and quenched and tempered grades which are somewhat similar to ABS Grade B and AH 36, it was found that the degree of property improvement was significantly greater in the plain carbon grade. This was true for both weld metal and HAZ impact properties. In the present investigation, significant differences in the effect of metal powder additions on weldment properties were observed for Grade B and AH 36 plate. In Grade B plate, weld metal and HAZ impact properties were generally improved by the addition of metal powder filler. In Grade AH 36 plate however, some procedures resulted in increases in either weld metal or HAZ impact strength while others resulted in a decrease of both. NO general trend is apparent in the data on Grade AH 36 weldment properties. Further study of the effect of metal powder additions on the properties of high impact strength ABS grades is clearly warranted as is a further investigation of methods to improve weld metal soundness when electroslag and electrogas welds are produced with metal powder filler additions.

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TABLES

Table I Welding Process Parameters

Common to All Tests for 0.50 Root Opening
(Except Where Otherwise Noted)

Root Opening (in.)	0.50
Electrode Angle	10" from Vertical
Electrode Stickout (in.)	2.0
Shoe Length, Fixed (in.)	17.0
Shoe Length, Moving (in.)	4.50
Reinforcement (in.)	0.063 (1/16)
Water Flow Rate (gpm)	0.75
Electrode Diameter (in.)	0.094 (3/32)
Oscillation Frequency (cpm)	25.0
Oscillation Amplitude (in.)	0.125
Flux Depth (in.)	0.625

Table II Welding Parameters

Hobart Fabco 81 Electrode

Plate Grade	ABS Grade B				
Tickness (in.)	0.75				
Joint Design	Single Bevel, 25° Included Angle, 0.50 in. Root Opening				
Electrode	Hobart Fabco 81				
Flux	NONE				
Metal Powder	Hobart 525				
Shielding Gas Flow Rate (cfh.)	5.0				
Voltage (V,DCRP)	30	32	32	35	38
Amperage (A)	475	625	575	575	600
Travel Speed (ipm.)	2.75	3.50	4.13	4.94	5.0
Metal Powder/Electrode Weight Ratio	0	0.31	0.50	0.85	1.0
Total Metal Deposition Rate (lbs/hr.)	33.75	44.21	50.62	62.43	67.50
Heat Input (J/in.)	311,000	343,000	268,000	244,000	273,000

Table III As-Welded Mechanical Properties

Hobart Fabco 81 Electrode

	0 Ratio	0.5 Ratio	0.85 Ratio
Yield Strength (psi.)	52,600*	44,700*	42,900*
Tensile Strength (psi.)	66,100*	68,500*	62,700*
Elongation (%)	33.5*	31.4*	9.7*
Brinell Hardness (BEN)			
Weld Metal	207	201	1.82
Heat Affected Zone	-	-	
Base Metal	128	128	128
CVN Impact Test Temperature (°F)	+32	+32	+32
CVN Impact Strength (ft-lbs.)			
Weld Metal	20,21,22 Avg.21	31.5,33,43 Avg.35.8	19,20,31 Avg.23.3
Heat Affected Zone	80,94,94 Avg.89.3	100,110,113 Avg.107.7	80,81,83 Avg.81.3
Base Metal -	68,69,71 Avg. 69.3		

Transverse Orientation, All Failures in Parent Metal

Table IV Welding Parameters

Hobart PS 588 Electrode

Plate Grade	ABS Grade B			
Thickness (in.)	0;75			
Joint Design	Single Bevel, 25° Included Angle, 0.50 in. Root Opening			
Electrode	Hobart PS 588			
Flux	Linde 124			
Metal Powder	Hobart 525			
Shielding Gas Flow Rate (cfh.)	5.0			
Voltage (V,DCRP)	32	40	40	40
Amperage (A)	500	. 600 -	600	600
Travel Speed (ipm.)	3.0	4.0	4.9	5.3
Metal Powder/Electrode Weight Ratio	0.25	0.50	0.83	1 . 0
Total Metal Deposition Rate (lbs/hr.)	28.10	50.62	61.80	67.50
Heat Input (J/in.)	320,000	360,000	294,000	272,000

Table V Welding Parameters

Airco Supercore Electrode

Plate Grade	ABS Grade B			
Tickness (in.)	0.75			
Joint Design	Single Bevel, 25° Included Angle, 0.50 in. Root Opening			
Electrode	Airco Supercore			
Flux	Linde 124			
Metal Powder	Hobart 525			
Shielding Gas Flow Rate (cfh.)	5.0			
Voltage (V, DCRP)	33	33	33	38
Amperage (A)	600	625	650	650
Travel Speed (ipm.)	2.25*	4.75**	5.50	4.50*
Metal Powder/Electrode Weight Ratio	.42	.70	.75	.80
Total Metal Deposition Rate (lbs/hr.)	40.50	48.40	49.80	51.30
Heat Input (J/in.)	528,000	261,000	234,000	329,000

0.625 in. root opening, 25° included angle

0.625 in. root opening, square butt

Table VI Welding Parameters

Lincoln 431 Innershield Electrode

Plate Grade	ABS Grade B		
Thickness (in.)	0:75		
Joint Design	Single Bevel, 25° Included Angle, 0.50 in. Root Opening		
Electrode	Lincoln 431		
Flux	NONE		
Metal Powder	Hobart 525		
Shielding Gas Flow Rate (cfh.)	20.0		
Voltage (V,DCRP)	33	37	40
Amperage (A)	500	500	525
Travel Speed (ipm.)	3.0	4.25	4.25
Metal Powder/Electrode Weight Ratio	0	0.50	0.50
Total Metal Deposition Rate (lbs/hr.)	37.50	56.25	59.0
Heat Input (J/in.)	330,000	261,000	296,000

Table VII Welding Parameters

McKay 215463-ES Electrode

Plate Grade	ABS Grade AH36		
Tickness (in.)	0:75		
Joint Design	Single Bevel, 25° Included Angle, 0.375 in. Root Opening		
Electrode	McKay 215463-ES		
Flux	Arcos BV		
Metal Powder	Hobart 525		
Shielding Gas Flow Rate (cfh.)	5.0		
Voltage (V,DCRP)	39	40	40
Amperage (A)	475	575	525
Travel Speed (ipm.)	2.68	4.25	4.0
Metal Powder/Electrode Weight Ratio	0	0.40	0.50
Total Metal Deposition Rate (lbs/hr.)	33.75	51.75	50.63
Heat Input (J/in.)	414,700	324,000	315,000

Table VIII As-Welded Mechanical Properties

McKay 215463-ES Electrode

	O Ratio	0.5 Ratio
Yield Strength (psi.)	52,600	62,600
Tensile Strength (psi.)	71,400	71,400
Elongation (%)	28.5	24.5
Brinell Eardness (BHN)		
Weld Metal	166	156
Heat Affected Zone		
Base Metal	170	169
CVN Impact Test Temperature (“F)	-4	-4
CVN Impact Strength (ft-lbs.)		
Weld Metal	28,30,38 Avg. 32	21,24,34 Avg. 26.3
Heat Affected Zone	10,13,15 Avg. 12.7	16,17.5,18 Avg. 17.2
Base Metal	18,18,24 Avg. 20	

Table Ix Welding Parameters

Linde MC 70 Electrode

Plate Grade	ABS Grade AH36		
Thickness (in.)	0.75		
Joint Design	Single Bevel, 25° Included Angle, 0.375 in. Root Opening		
Electrode	Linde MC 70		
Flux	Linde 124		
Metal Powder	Hobart 525		
Shielding Gas Flow Rate (cfh.)	12.0		
Voltage (V,DCIQ)	36	36	38
Amperage (A)	450	475	475
Travel Speed (ipm.)	3.0	3.0*	3.75*
Metal Powder/Electrode Weight Ratio	0	0.47	0.85
Total Metal Deposition Rate (lbs/hr.)	22.50	33.0	41.63
Heat Input (J/in.)	324,000	342,000	288,800

0.50 in. Root Opening

Table X As-Welded Mechanical Properties

Linde MC 70 Electrode

	0 Ratio	0.47 Ratio	0.86 Ratio
Yield Strength (psi.)	57,300	57,100	57,500
Tensile Strength (psi.)	78,100	77,700	79,400
Elongation (%)	23.6	23.3	24.0
Brinell Hardness (BHN)			
Weld Metal	165	147	150
Heat Affected Zone	176	176	153
Base Metal	153	132	147
CVN Impact Test Temperature (“F)	-4	-4	-4
CVN Impact Strength (ft-lbs.)			
Weld Metal	14,18,26 Avg.19.3	8,40,40 Avg. 29.3	25,38,42 Avg.34.3
Heat Affected Zone	36,40,50 Avg.42.0	12,15,16 Avg.14.3	14,14,23 Avg.17.0
Base Metal	12,12,12 Avg.12.0		

Table XI Welding Parameters

Linde 29S Electrode

Plate Grade	ABS Grade AH36		
Thickness (in.)	0:75		
Joint Design	Single Bevel, 25° Included Angle, 0.375 in. Root Opening		
Electrode	Linde 29S		
Flux	Linde 124		
Metal Powder	Hobart 525		
Shielding Gas Flow Rate (cfh.)	12.0		
Voltage (V,DCRP)	36	36	38
Amperage (A)	500	625*	550*
Travel Speed (ipm.)	2.0	4.0	4.0
Metal Powder/Electrode Weight Ratio	0	0.54	0.98
Total Metal Deposition Rate (lbs/hr.)	25.50	39.27	50.49
Heat Input (J/in.)	540,000	337,500	313,500

2.50-3.00 in. Electrode Extension

Table XII As-Welded Mechanical Properties

Linde 29S Electrode

	Ratio	0.54 Ratio	0.98 Ratio
Yield Strength (psi.)	54,400	53,900	54,900
Tensile Strength (psi.)	76,100	76,100	74,600
Elongation (%)	21.3	21.5	19.2
Brinell Hardness (BHN)			
Weld Metal	153	156	153
Heat Affected Zone	176	170	170
Base Metal	144	150	141
CVN Impact Test Temperature (°F)	-4	-4	- 4
CVN Impact Strength (ft-lbs)			
Weld Metal	20,39,42 Avg.33.7	25,25,27 Avg.25.7″	28,36,40 Avg.34.7
Heat Affected Zone	13,14,25 Avg.17.3	30,36,48 Avg.38	2,3,24 Avg.9.7
Base Metal	12,12,12 Avg.12.0		

Table XIII Welding Parameters

Lincoln 431 Innershield

Plate Grade	ABS Grade AH36			
Thickness (in.)	0.75			
Joint Design	Single Bevel, 25° Included Angle, 0.375 in. Root Opening			
Electrode	Lincoln 431 Innershield			
Flux	NONE			
Metal Powder	Hobart 525 or Tapco High Al.			
Shielding Gas Flow Rate (cfh.)	25.0			
Voltage (V,DCRP)	36	40	40	42
Amperage (A)	525	575	575	600
Travel Speed (ipm.)	2.75	4.0	4.5	5.0
Metal Powder/Electrode Weight Ratio	0	.50*	.50**	.80*
Total Metal Deposition Rate (lbs/hr.)	33.75	50.62	50.62	60.75
Heat Input (J/in.)	412,400	345,000	306,000	302,000

Hobart 525 Powder

Tapco High Al. Powder

Table XIV As-Welded Mechanical Properties

Lincoln 431 Innershield Electrode

	0 Ratio	0.5 Ratio	0.5 Ratio (High Al Powder)
Yield Strength (psi.)	60,700	59,100	60,100
Tensile Strength (psi.)	79,000	77,000	81,000
Elongation (%)	27.4	26.3	24.9
Brinell Hardness (Em)			
Weld Metal	131	174	174
Heat Affected Zone			
Base Metal	168	170	167
CVN Impact Test Temperature (“F)	-4	-4	-4
CVN Impact Strength (ft-lbs)			
Weld Metal	47,55,60 Avg.54	31,40,41 Avg.37.3	23,25,30 Avg.26
Heat Affected Zone	60,75,75 Avg.70	13,24,60 Avg.32.3	11,12,15 Avg.12.7
Base Metal			

Table XV Welding Parameters

Airco Metal Core 6 Electrode

Plate Grade	ABS Grade B	
Thickness (in.)	0:75	
Joint Design	Single Bevel, 25° Included Angle, 0.375 in. Root Opening	
Electrode	Airco 6	
Flux	NONE (see text)	
Metal Powder	Hobart 525	
Shielding Gas Flow Rate (cfh.)	35.0	
Voltage (V,DCRP)	36	38
Amperage (A)	450	525
Travel Speed (ipm.)	2.0	3.0
Metal Powder/Electrode Weight Ratio	0	0.50
Total Metal Deposition Rate (lbs/hr.)	17.60	26.40
Heat Input (J/in.)	486,000	399,000

Table XVI As-welded Mechanical Properties

Airco Metal Core 6 Electrode

	o Ratio	0.50 Ratio
Yield Strength (psi.)	49,900	48,900
Tensile Strength (psi.)	73,600	57,200
Elongation (%)	18.3	4.7
Brinell Hardness (BHN)		
" Weld Metal	165	190
Heat Affected Zone	156	147
Base Metal	134	132
CVN Impact Test Temperature (°F)	+32	+32
CVN Impact Strength (ft-lbs.)		
Weld Metal	14,15,20 Avg.16.3	20,26,40 Avg. 28.7
Heat Affected Zone	17,23,37 Avg. 25.7	14,24,24 Avg20.7
Base Metal	18,18,20 Avg. 18.7	

Table XVII Welding Parameters

Hobart Fabco 81 Electrode
23.0 in. Plate Length

Plate Grade	ABS Grade B
Thickness (in.)	0.75
Joint Design	Single Bevel, 25° Included Angle, 0.375 in. Root Opening
Electrode	Hobart Fabco 81
Flux	NONE
Metal Powder	Hobart 525
Shielding Gas Flow Rate (cfh.)	12.5
Voltage (V, DCRP)	34
Amperage (A)	575
Travel Speed (ipm.)	4.5
Metal Powder/Electrode Weight Ratio	0.50
Total Metal Deposition Rate (lbs/hr.)	50.63
Heat Input (J/in.)	261,000

Table XVIII As-Welded Mechanical Properties

Hobart Fabco 81 Electrode, 23.0 in. Plate

	8.0 in. Location	" 18.0 in Location
Yield Strength (psi.)	65,500	63,900
Tensile Strength (psi.)	85,600	86,400
Elongation (%)	27	28
Brinell Hardness (BHN)		
Weld Metal		
Heat Affected Zone		
"Base Metal		
CVN Impact Test " Temperature ("F)	+32 .	+32
CVN Impact Strength (ft-lbs .)		
Weld Metal	36,34,36 Avg.35.3	"30.5,29.5,31 Avg.30.3.
Heat Affected Zone	42.5,23.5,28.5 Avg.31.5	33.5,25.5,32.5 Avg.30.5
Base Metal	27,27,24.5 Avg.26.2	

Table XIX Welding Parameters

Airco (Kobe) Metal Powder-Bearing Flux

Plate Grade	ABS Grade B	
Thickness (in.)	0.75	
Joint Design	Single Bevel. 25° Included Angle, 0.50 in.. Root Opening	
Electrode	Airco Supercore	
Flux	Airco (Linde 124 Starting)	
Metal Powder	Hobart 525	
Shielding Gas Flow Rate (cfh.)	5.0	
voltage (V,DCRP)	3.3	33
Amperage (A)	450	500
Travel Speed (ipm.)	2.50	4.0
Metal Powder/Electrode Weight Ratio	0	0.625
Total Metal Deposition Rate (lbs/hr.)	27.0	48.75
Heat Input (J/in.)	356,000	248;000

Table XX Welding Parameters

Linde 39B Metal Powder-Bearing Flux

Plate Grade	ABS Grade B	
Thickness (in.)	0.75	
Joint Design	Single Bevel, 25° Included Angle, 0.50 in. Root Opening	
Electrode	Airco Supercore	
Flux	Linde 39B (Linde 124 Starting)	
Metal Powder	Hobart 525	
Shielding Gas Flow Rate (cfh.)	5.0	
Voltage (V,DCRP)	33	38
Amperage (A)	450	500
Travel Speed (ipm.)	2.5	2.5*
Metal Powder/Electrode Weight Ratio	0	0.50
Total Metal Deposition Rate (lbs/hr.)	27.0	40.5
Heat Input (J/in.)	356,000	456;000

0.625 in. Root Opening

Table XXI Heat Affected Zone Width at Midplane of Plate

Electroslag Weldments

Electrode	Metal Powder Ratio	HAZ Width (in.)
Hobart Fabco 81	0.0	0.453
	0.50	0.512
	0.85	0.394
McKay 215463 ES	0.0	0.453
	0.50	0.354
Linde 29S	0.0	0.512
	0.54	0.413
	0.98	0.295
Linde MC 70	0.0	0.394
	0.47	0.374
	0.86	0.374

Table XXII Heat Affected Zone Width at Midplane of Plate

Electrogas Weldments

Electrode	Metal Powder Ratio	HAZ Width (in.)
Lincoln 431	0.0	0.413
	0.50	0.276
	0.50 (High A1 Powder)	0.315
Airco 6	0.0	0.453
	0.50	0.394

FIGURES

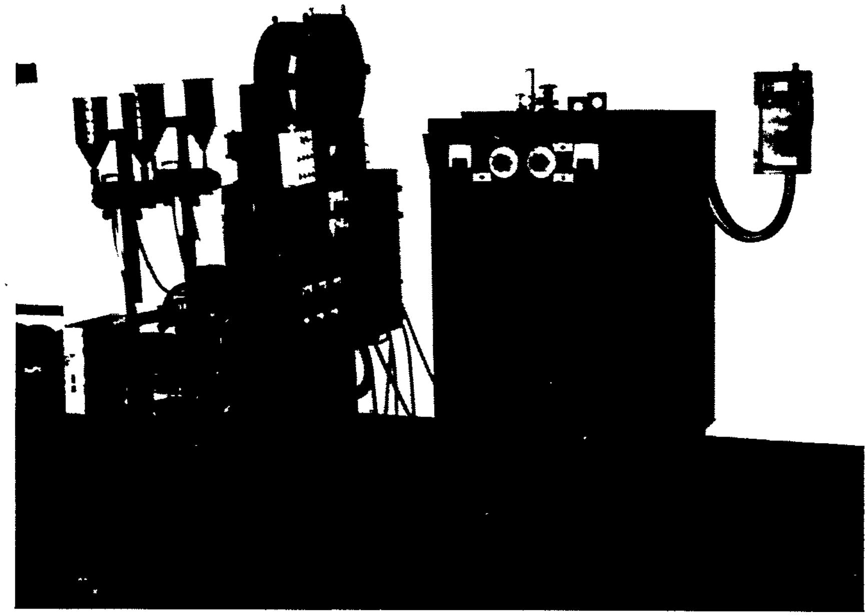


Figure 1. Overall View, Welding Head, Control Console With Walk-Around Box and Power Supply.

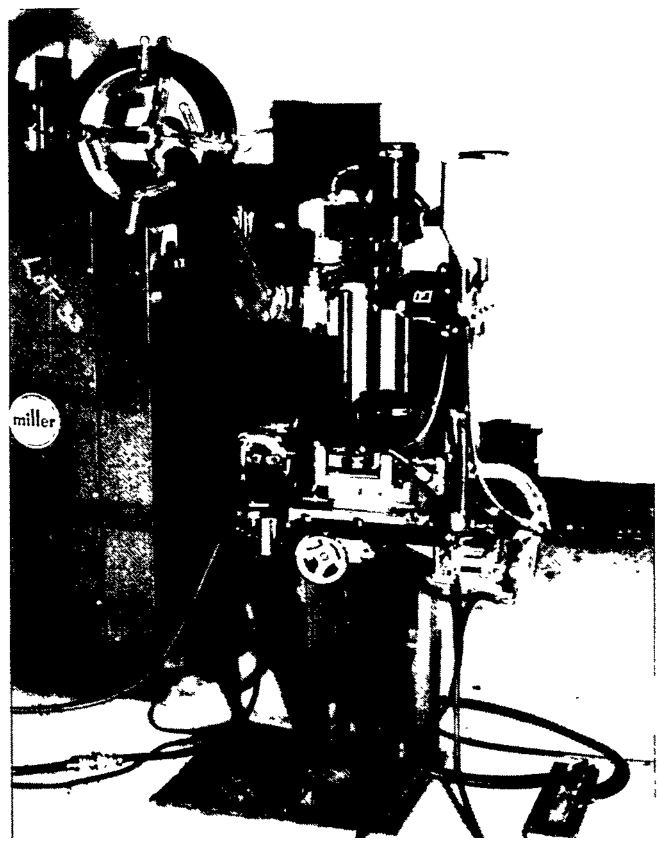


Figure . Welding Head.

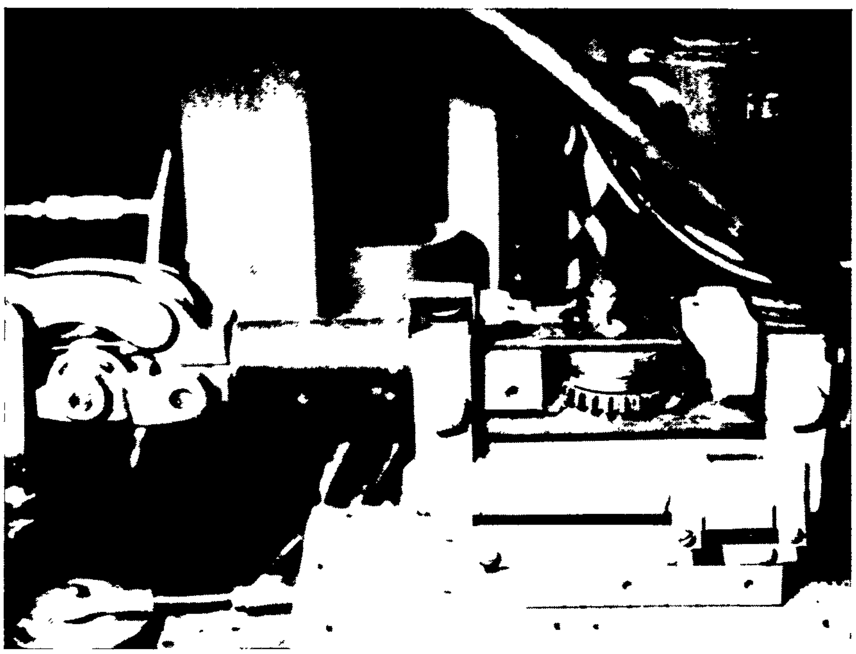


Figure 3. Wire Straightener and Feed Rolls. Oscillator Crank at Lower Left.

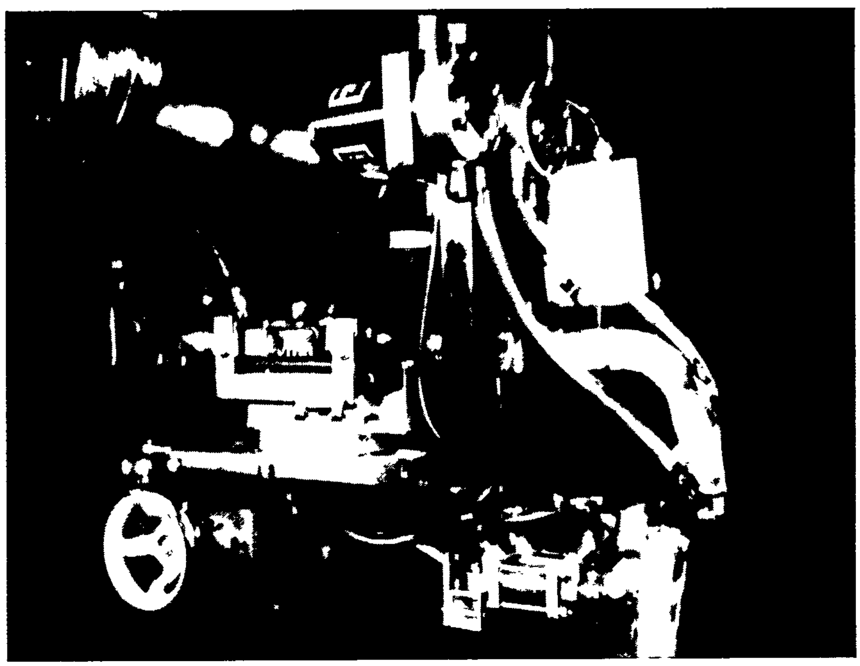
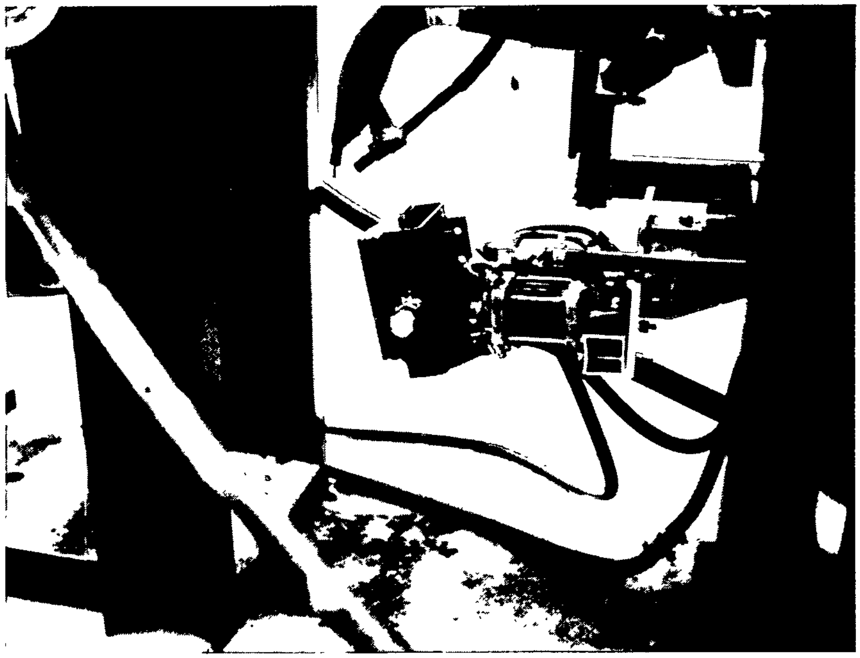


Figure 4. Front View of Welding Head Showing Metal Powder and Flux Dispensing Tubes.

Figure 5. Tapco Electronic Metering Devices for Flux (left) and Metal Powder (right). Note Shielding Gas-Line to Metal Powder Metering Device.



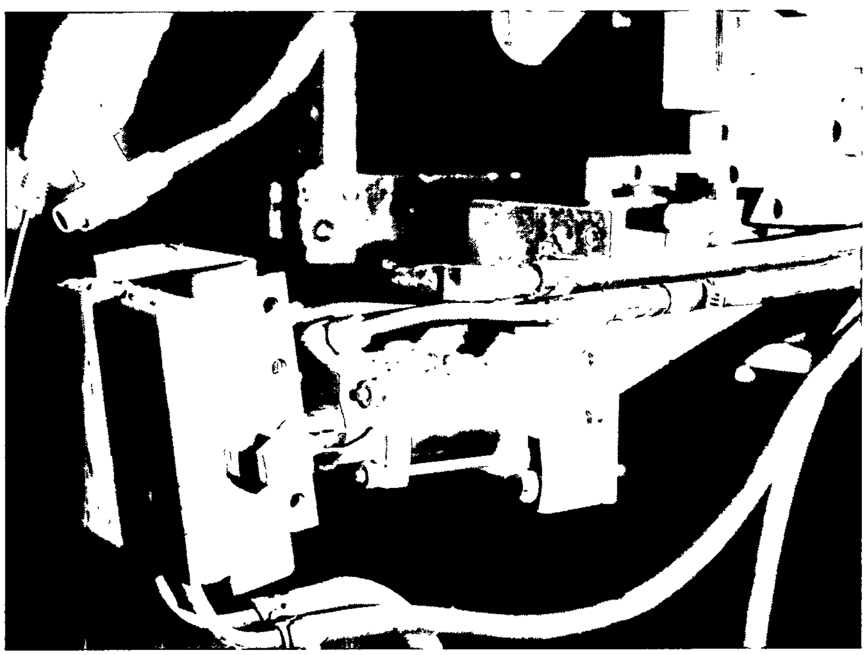


Figure 6. Two Views of Pneumatically-Actuated Moving Water-Cooled Shoe and Ceramic Nozzle for Dispensing Metal Powder to Electrode.

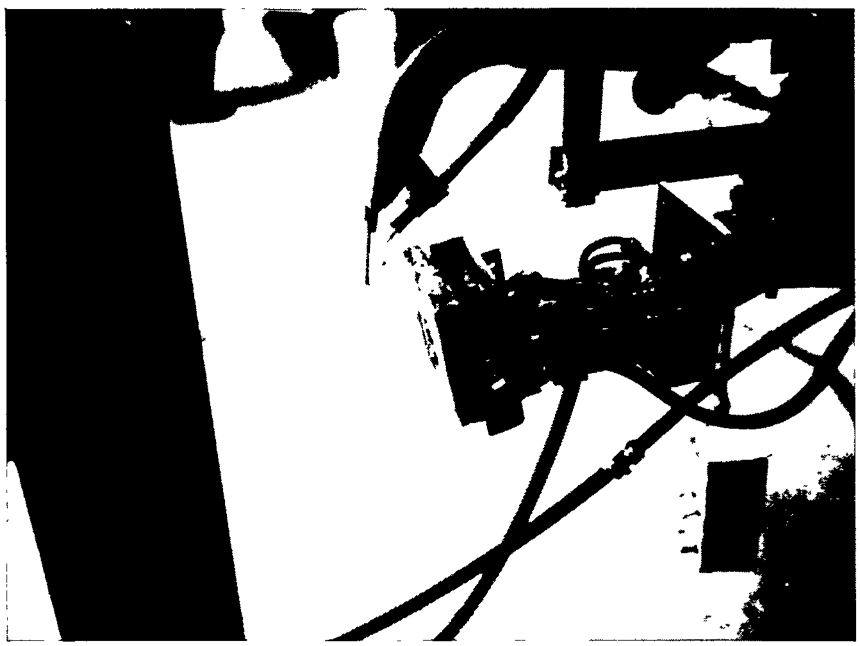
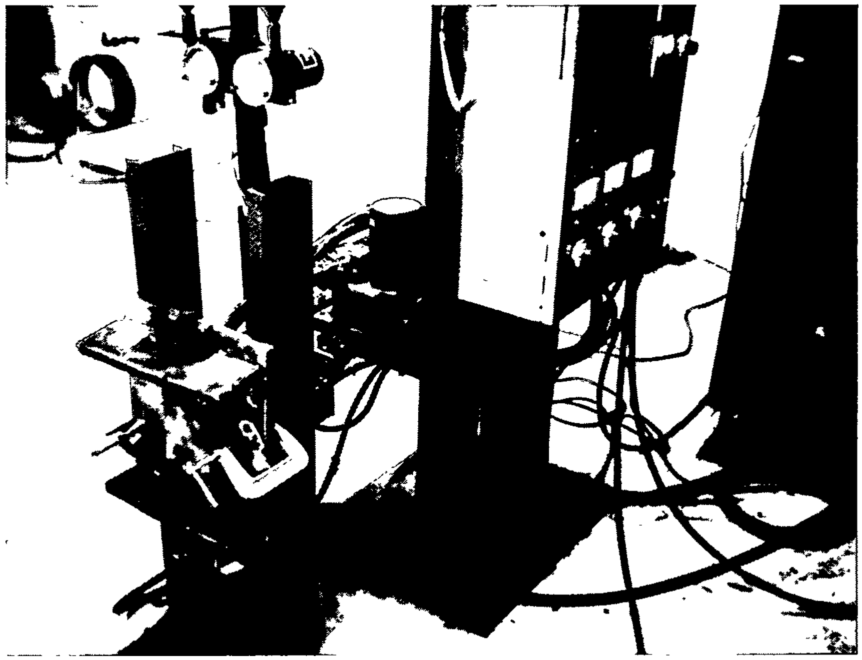


Figure 7. Dispensing Metal Powder With Shielding Gas.



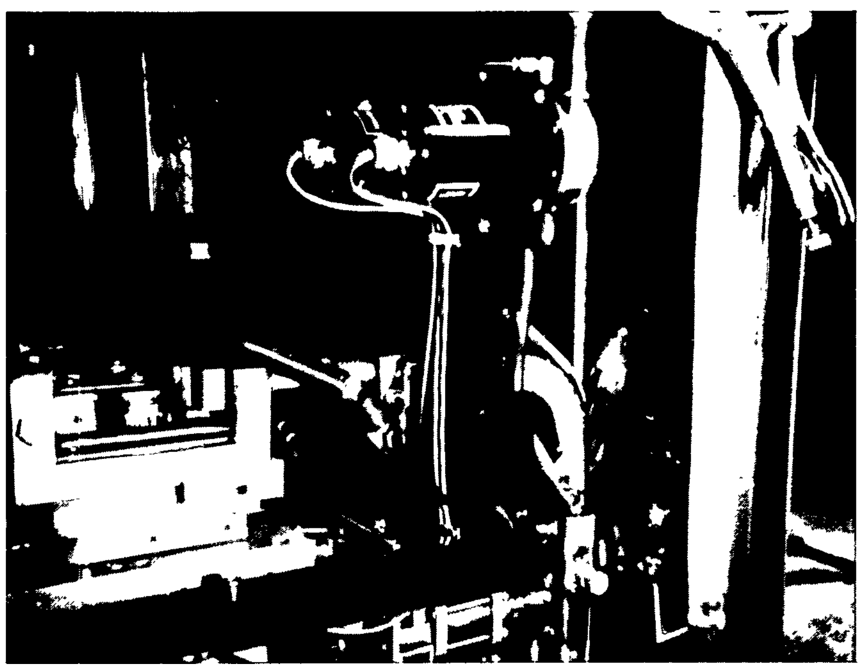


Figure 8. Two Views of Head in Position for Start of Welding 15.0 in. Plate.

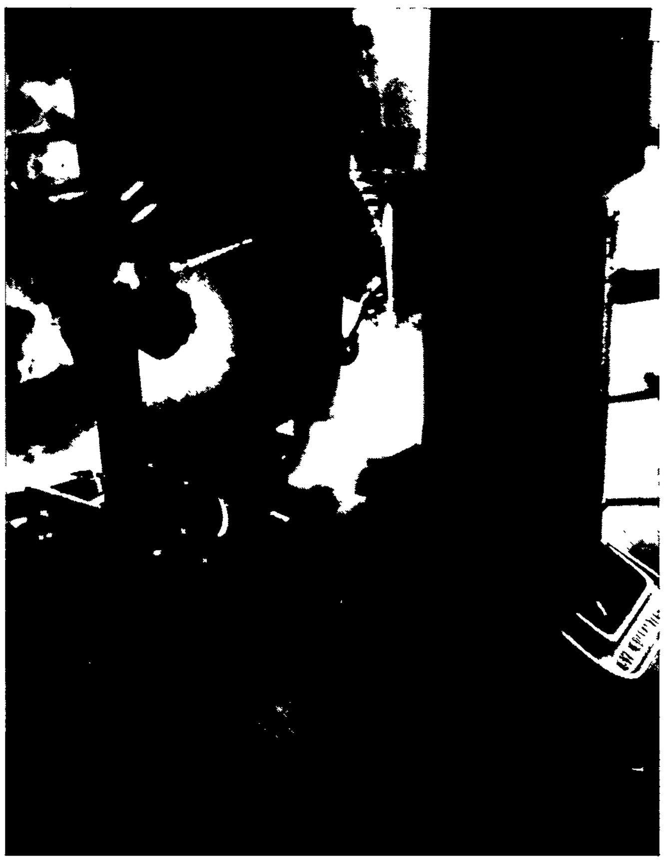


Figure 9. Mid-Point of Welding 15.0 in. Plate in Electroslag Mode.

Figure 10. Completion of Welding 15.0 in. Plate.

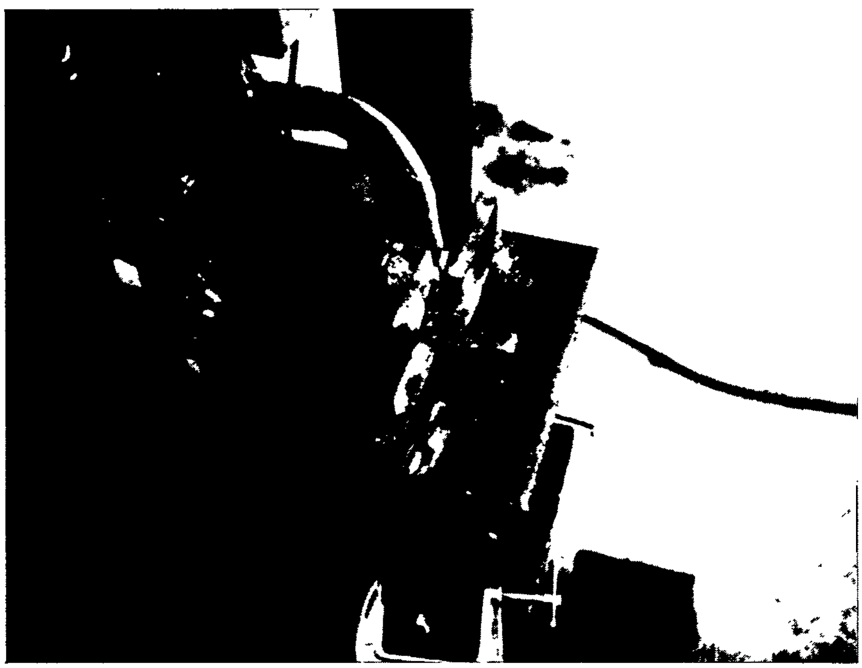


Figure 11. Completed Weld.

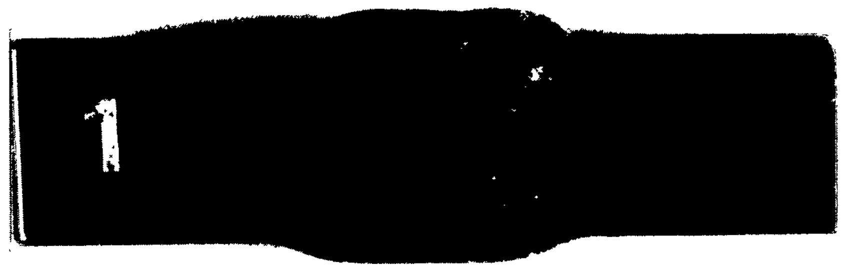


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Figure 12. Test Plate Welded With Hobart Fabco 81 Electrode.
Metal Powder Ratio 0.0.

Figure 13. Test Plate Welded With Hobart Fabco 81 Electrode.
Metal Powder Ratio 0.50.

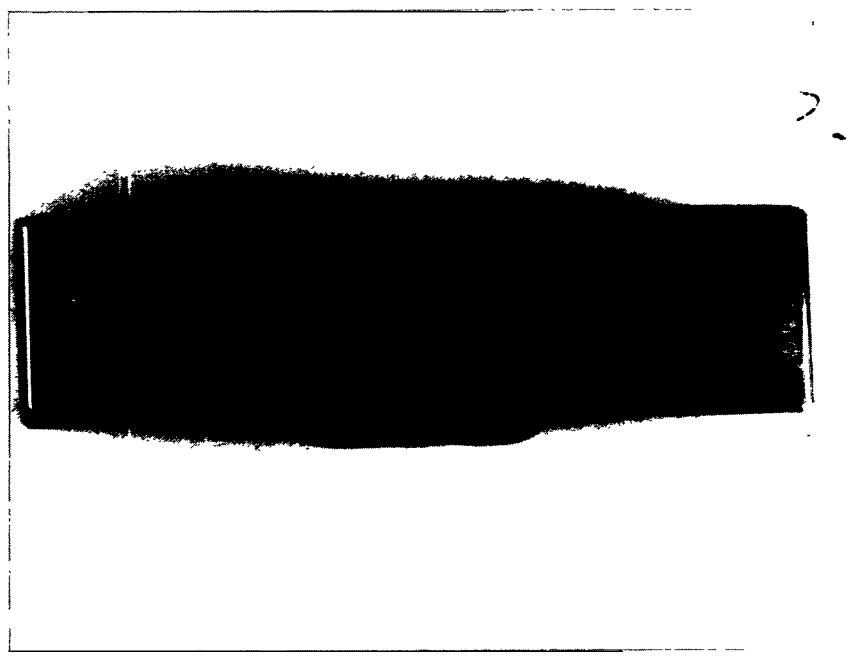


Figure 14. Test Plate Welded With Hobart Fabco 81 Electrode.
Metal Powder Ratio 0.85.

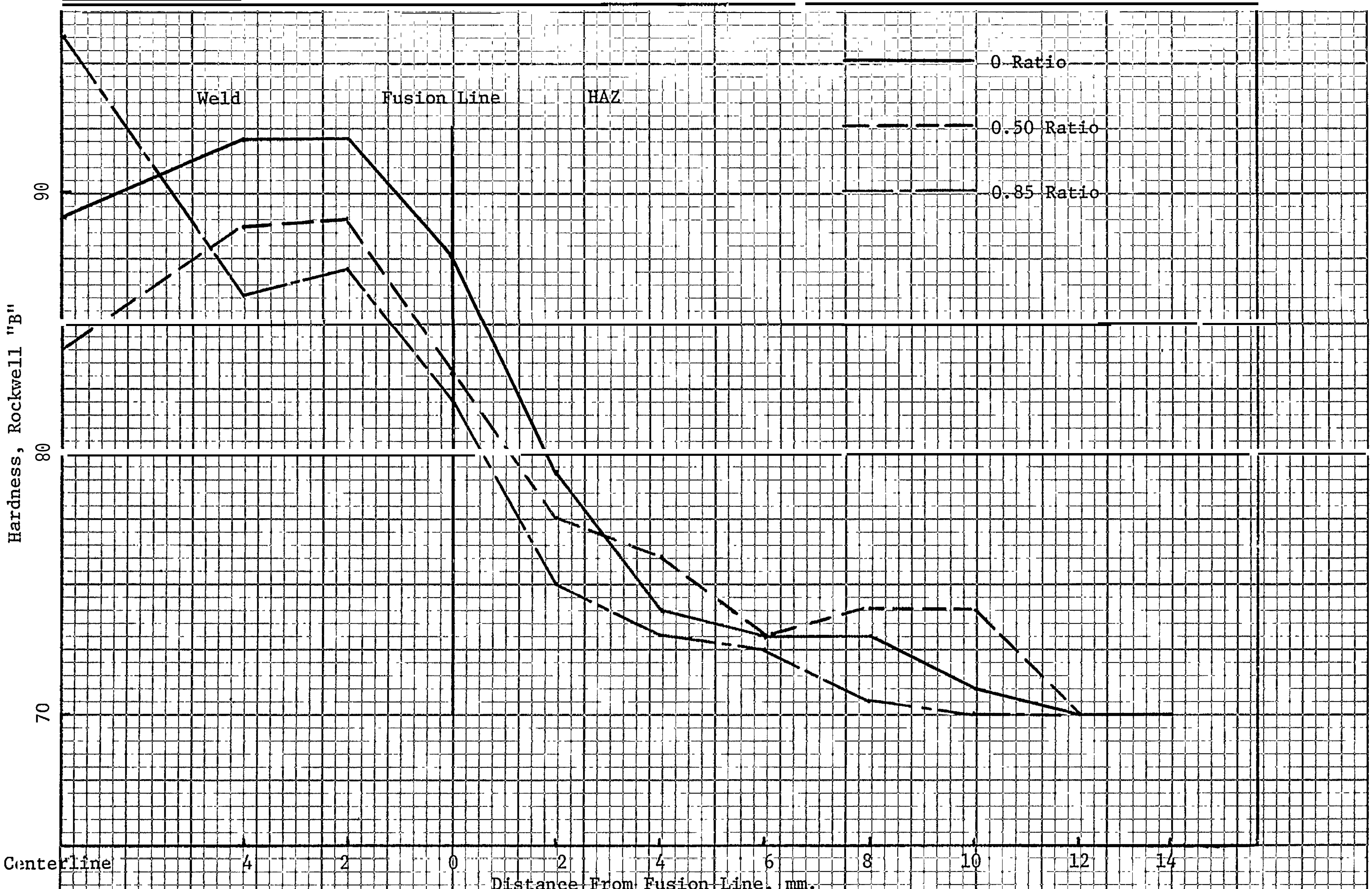


Figure 15. Hardness of Welds Produced With Hobart Fabco 81 Electrode

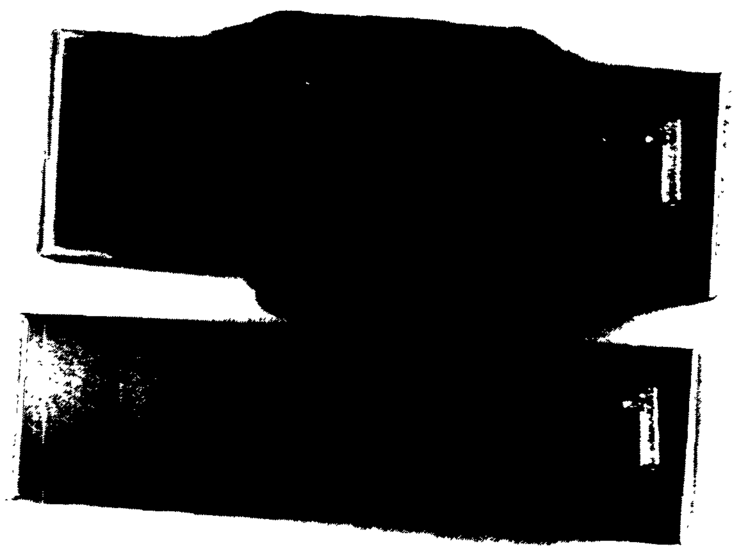


Figure 16. Test Plate Welded With McKay 215463 ES Electrode.
Metal Powder Ratio 0.0.

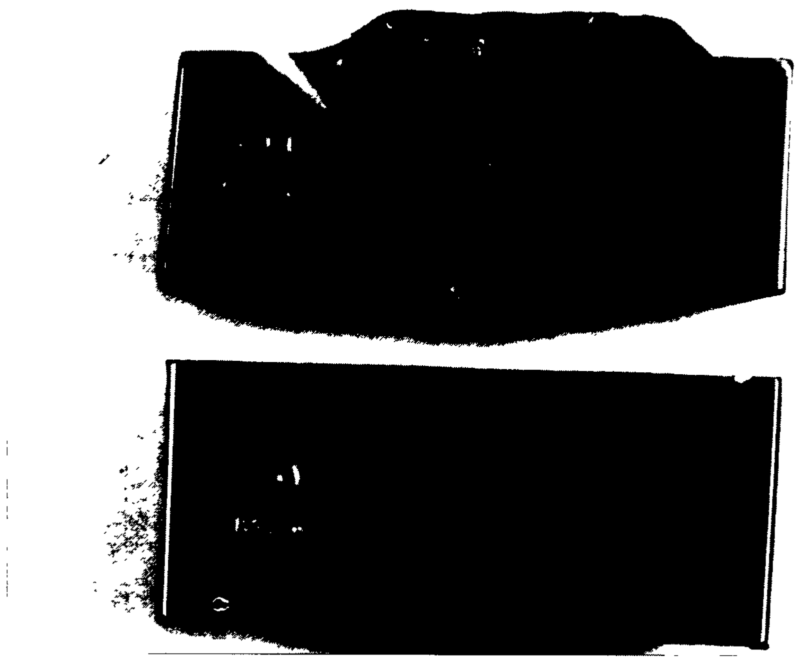
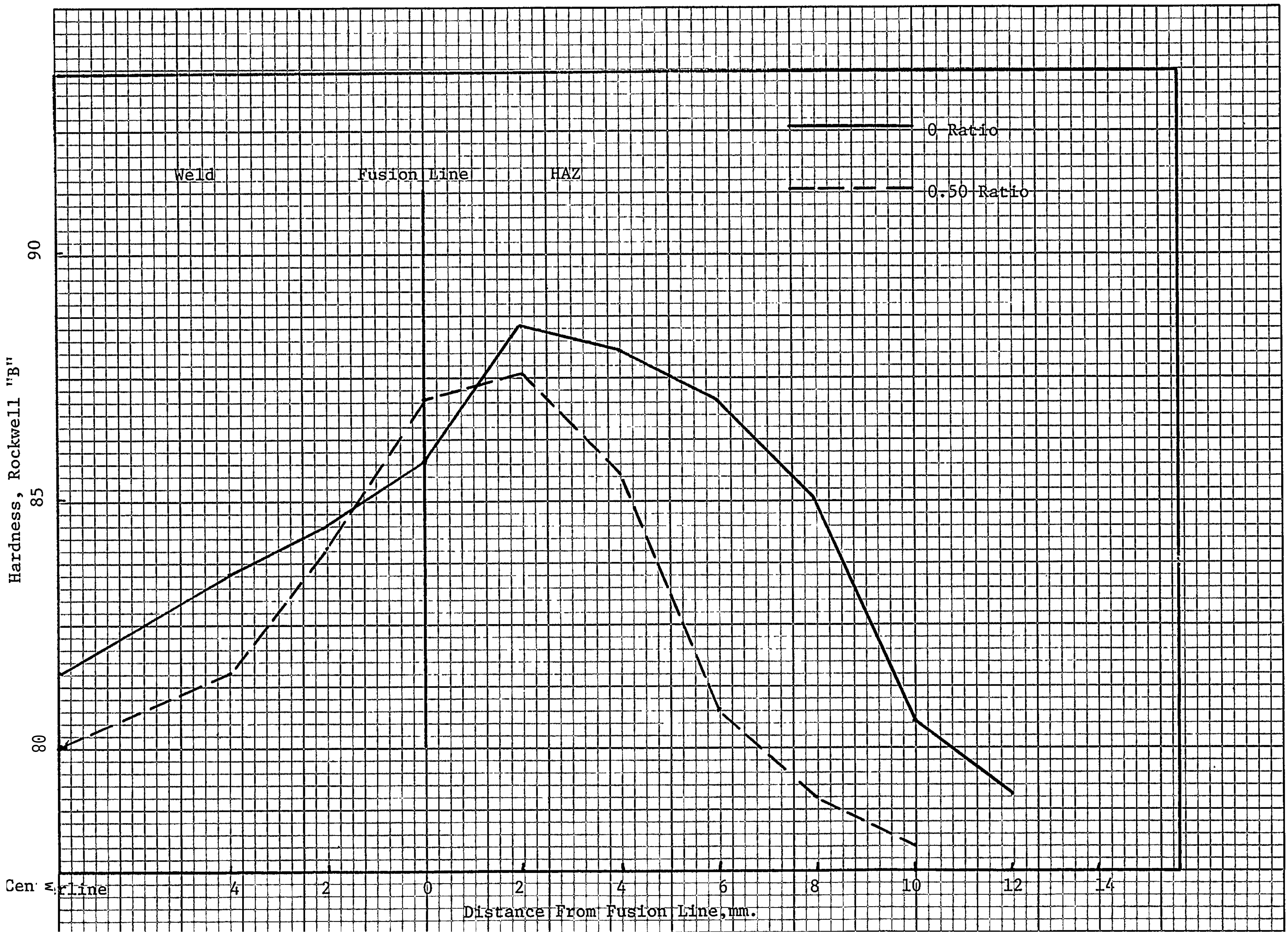


Figure 17. Test Plate Welded With McKay 215463 ES Electrode.
Metal Powder Ratio 0.50.


0 Ratio
0.50 Ratio
Weld
Fusion Line
HAZ
90
85
80
Hardness, Rockwell "B"
Centerline
4
2
0
2
4
6
8
10
12
14
Distance From Fusion Line, mm.

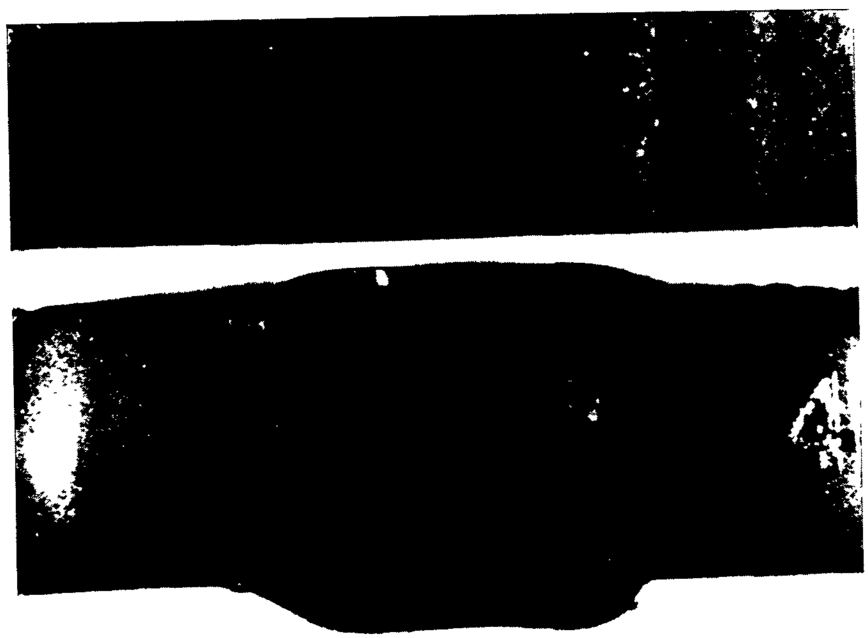


Figure 19. Test Plate Welded With Linde MC 70 Electrode.
Metal Powder Ratio 0.0.

Figure20. Test Plate Welded With Linde MC 70 Electrode.
Metal Powder Ratio 0.47.

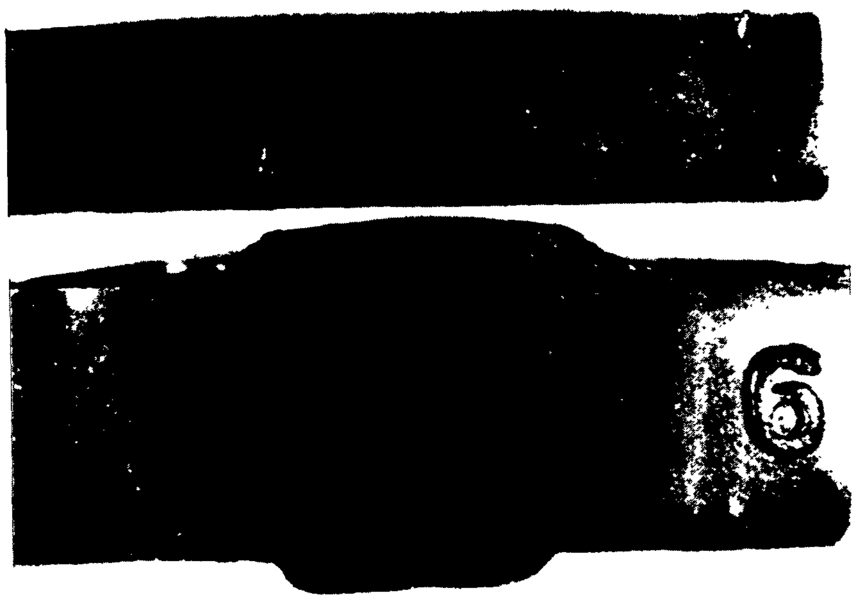
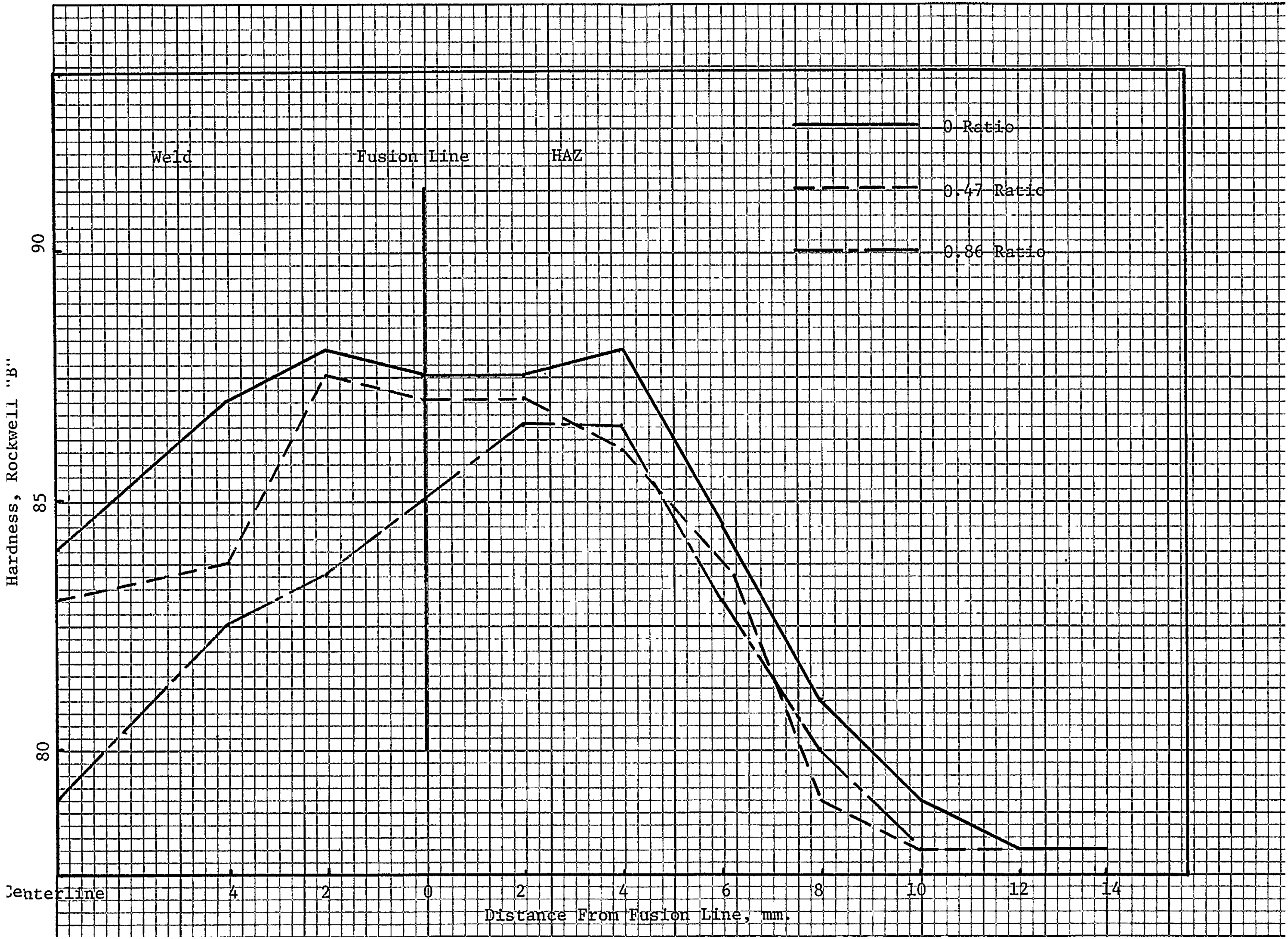


Figure 21. Test Plate Welded With Linde MC 70 Electrode.
Metal Powder Ratio 0.86.



Weld
Fusion Line
HAZ
0 Ratio
0.47 Ratio
0.86 Ratio
Hardness, Rockwell "B"
90
85
80
Centerline
4
2
0
2
4
6
8
10
12
14
Distance From Fusion Line, mm.

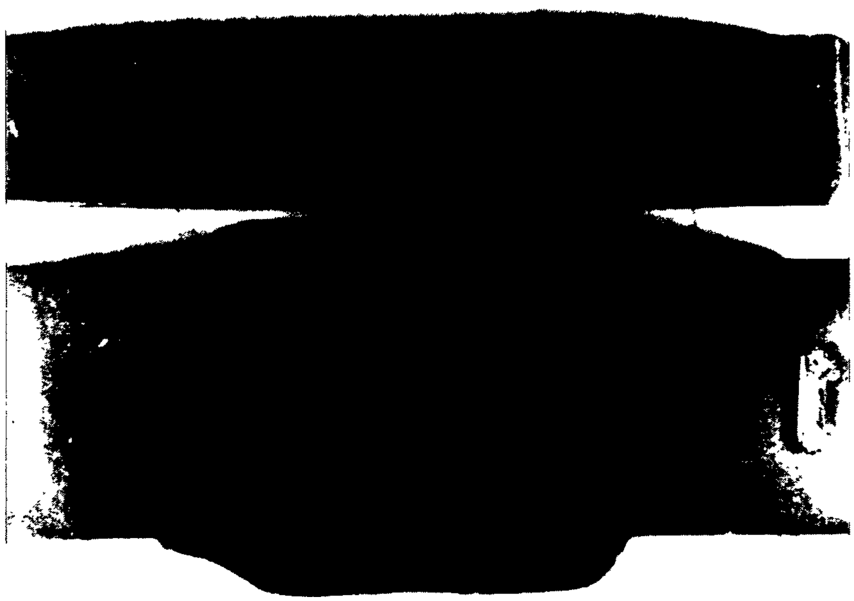


Figure 23. Test Plate Welded With Linde 29S Electrode.
Metal Powder Ratio 0.0.

Figure 24. Test Plate Welded With Linde 29S Electrode.
Metal Powder Ratio 0.54.

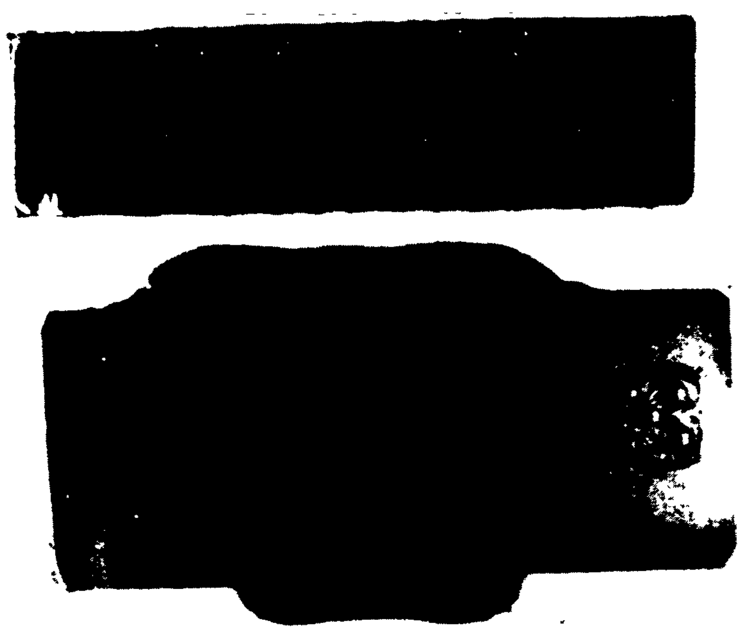
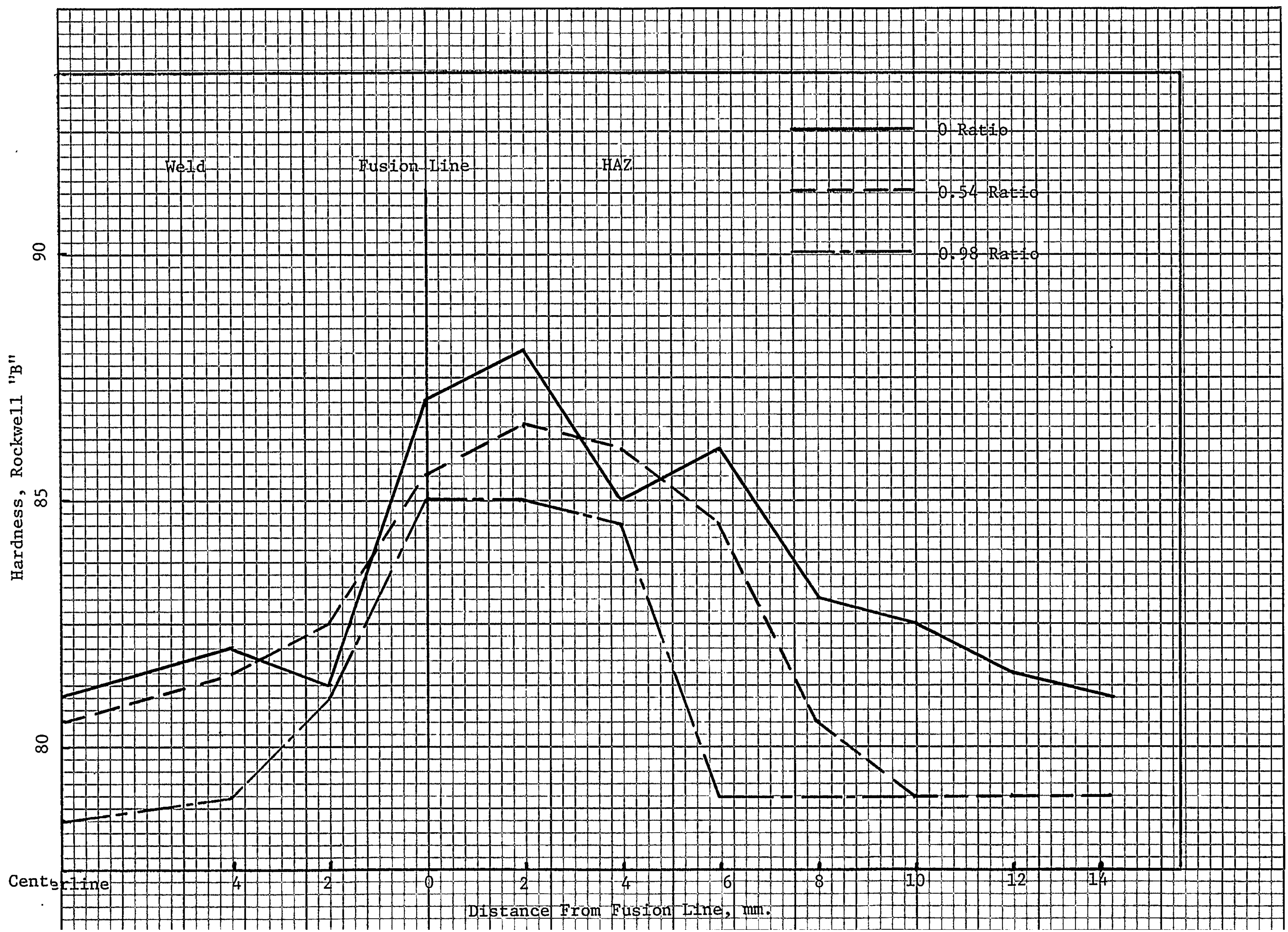


Figure 25. Test Plate Welded With Linde 29S Electrode.
Metal Powder Ratio 0.98.


0 Ratio
0.54 Ratio
0.98 Ratio
Weld
Fusion Line
HAZ
90
85
80
Hardness, Rockwell "B"
Centerline
4
2
0
2
4
6
8
10
12
14
Distance From Fusion Line, mm.

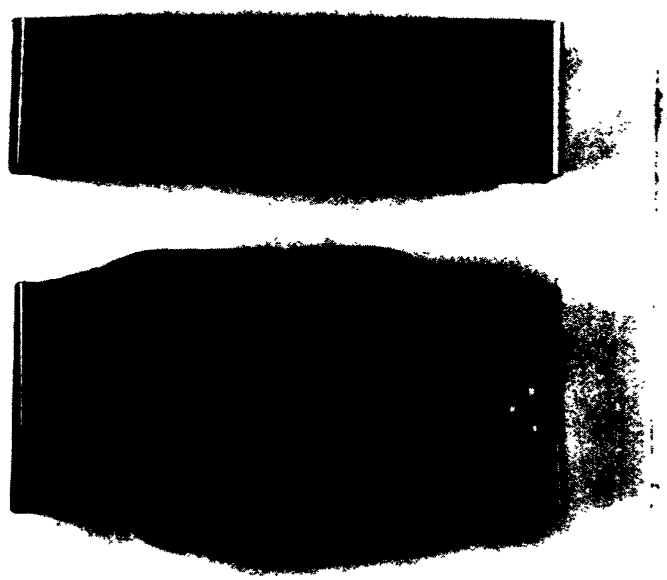


Figure27. Test Plate Welded With Lincoln 431 Electrode.
Metal Powder Ratio 0.0.

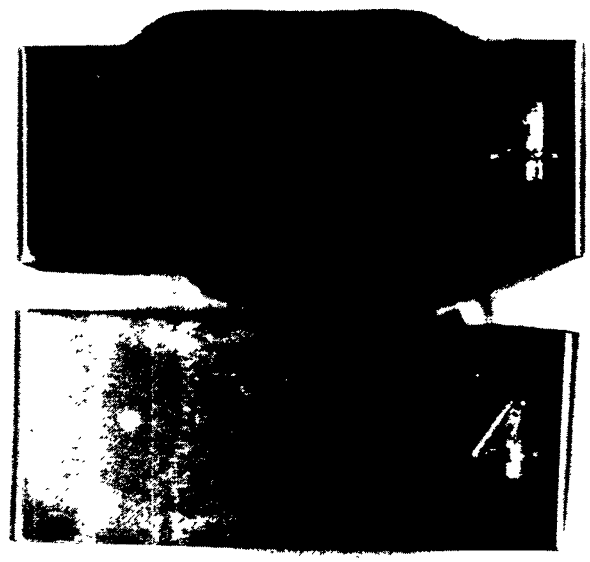


Figure 28. Test Plate Welded With Lincoln 431 Electrode. Metal Powder Ratio 0.50. (Hobart 525 Powder).

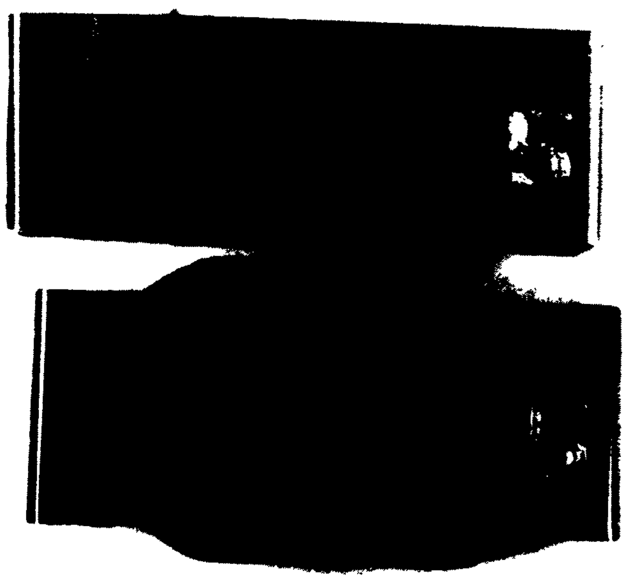


Figure 29. Test Plate Welded With Lincoln 431 Electrode.
Metal Powder Ratio 0.50 (High Al Powder).

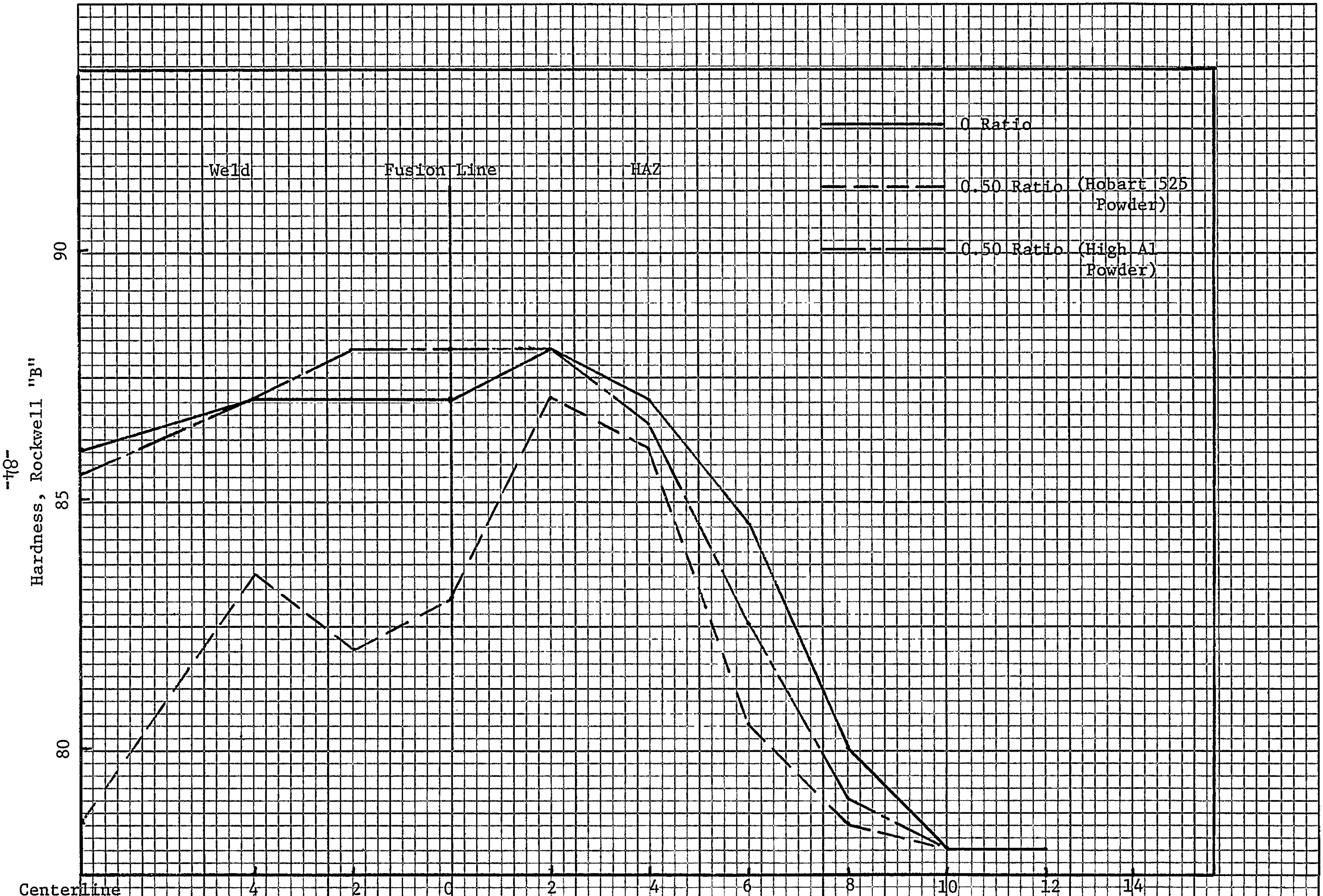


Figure 30. Hardness of Welds Produced With Lincoln 431 Electrode

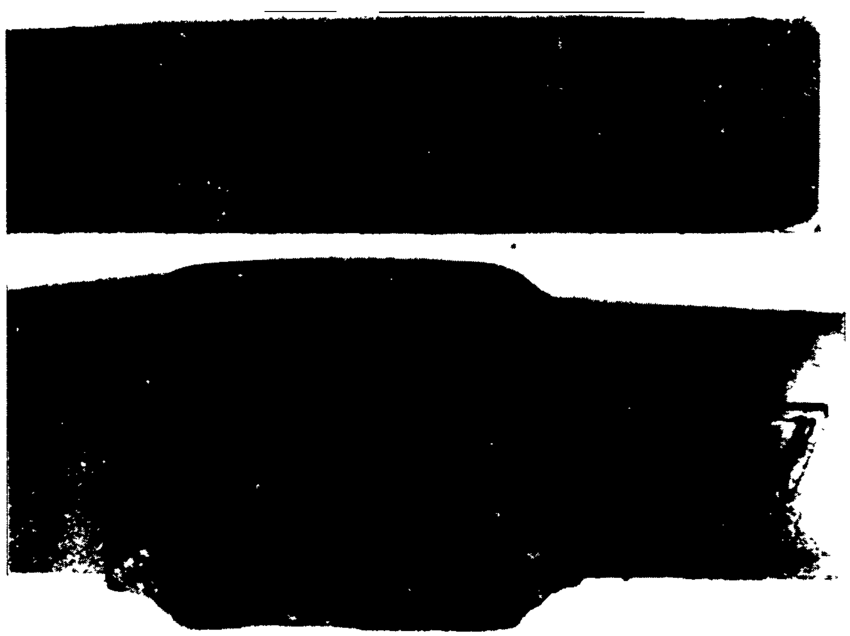


Figure 31. Test Plate Welded With Airco 6 Electrode.
Metal Powder Ratio 0.0.

Figure 32. Test Plate Welded With Airco 6 Electrode.
Metal Powder Ratio 0.50.

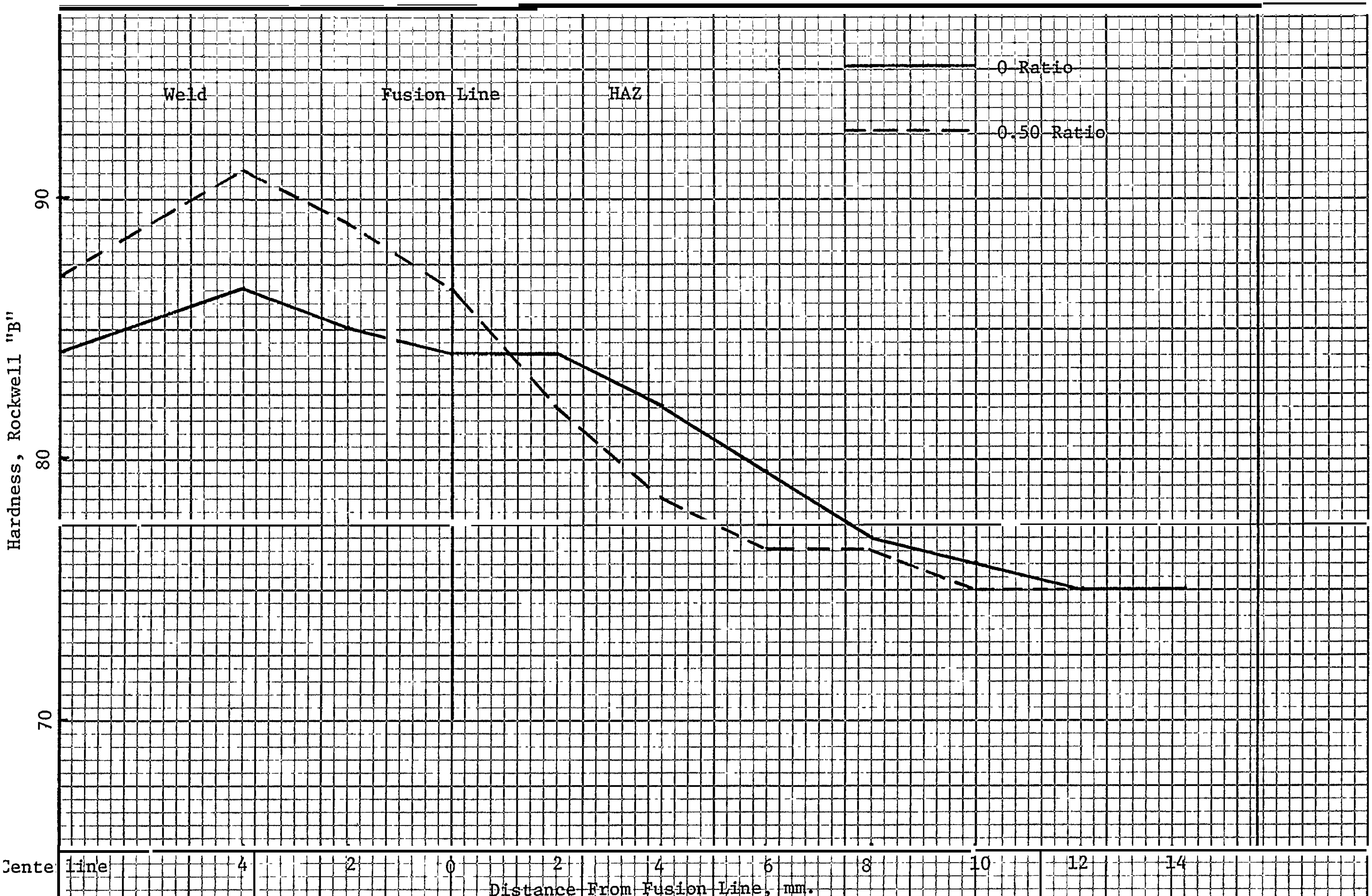


Figure 33. Hardness of Welds Produced With Airco 6 Electrode

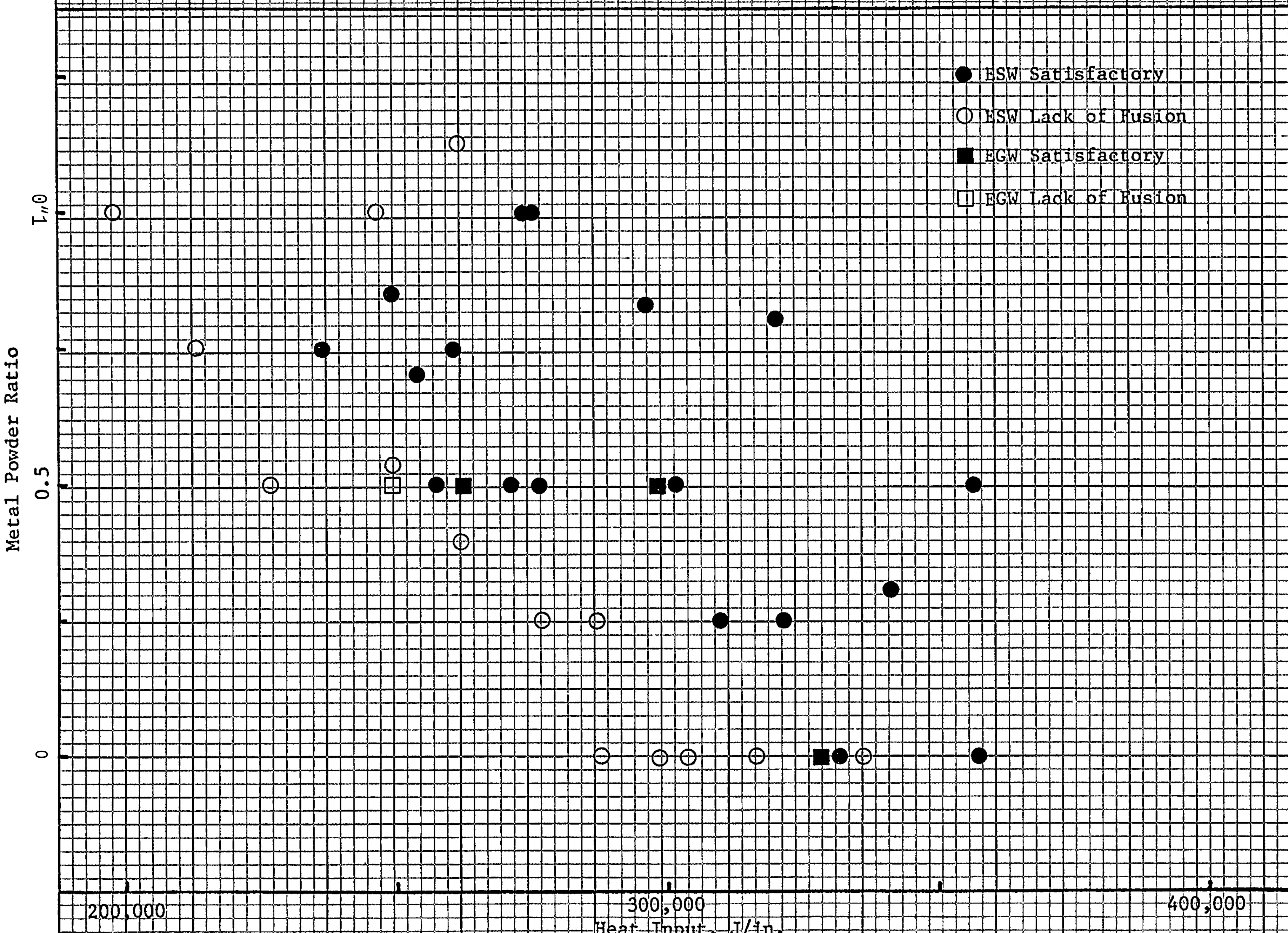


Figure 34. Metal Powder Ratio vs. Heat Input. 0.50 in. Root Opening. Solid Symbols Represent Satisfactory Welds. Open Symbols Represent Lack-of-Fusion Defects.

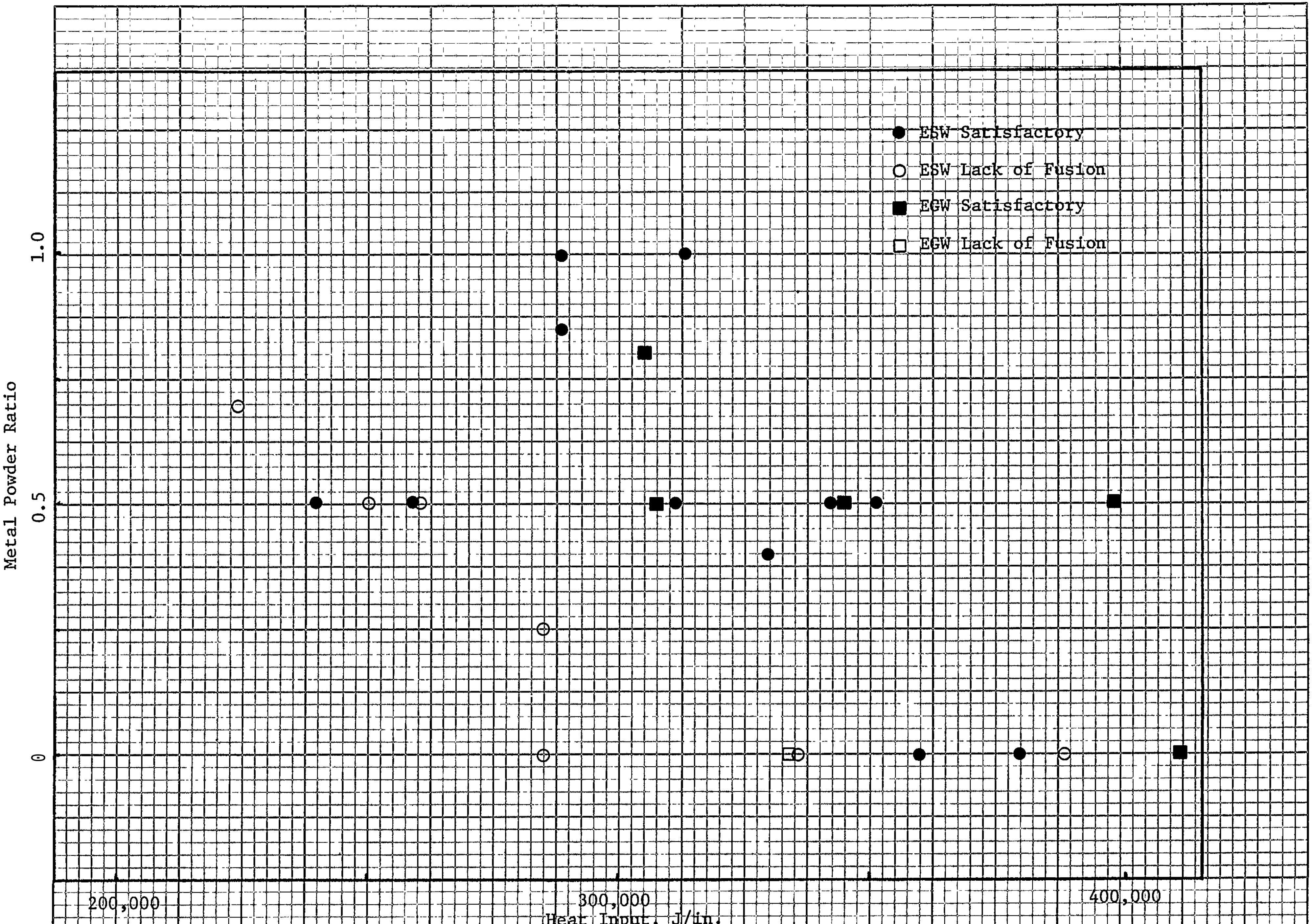


Figure 35. Metal Powder Ratio vs. Heat Input. 0.375 in. Root Opening. Solid Symbols Represent Satisfactory Welds. Open Symbols Represent Lack-of-Fusion Defects.

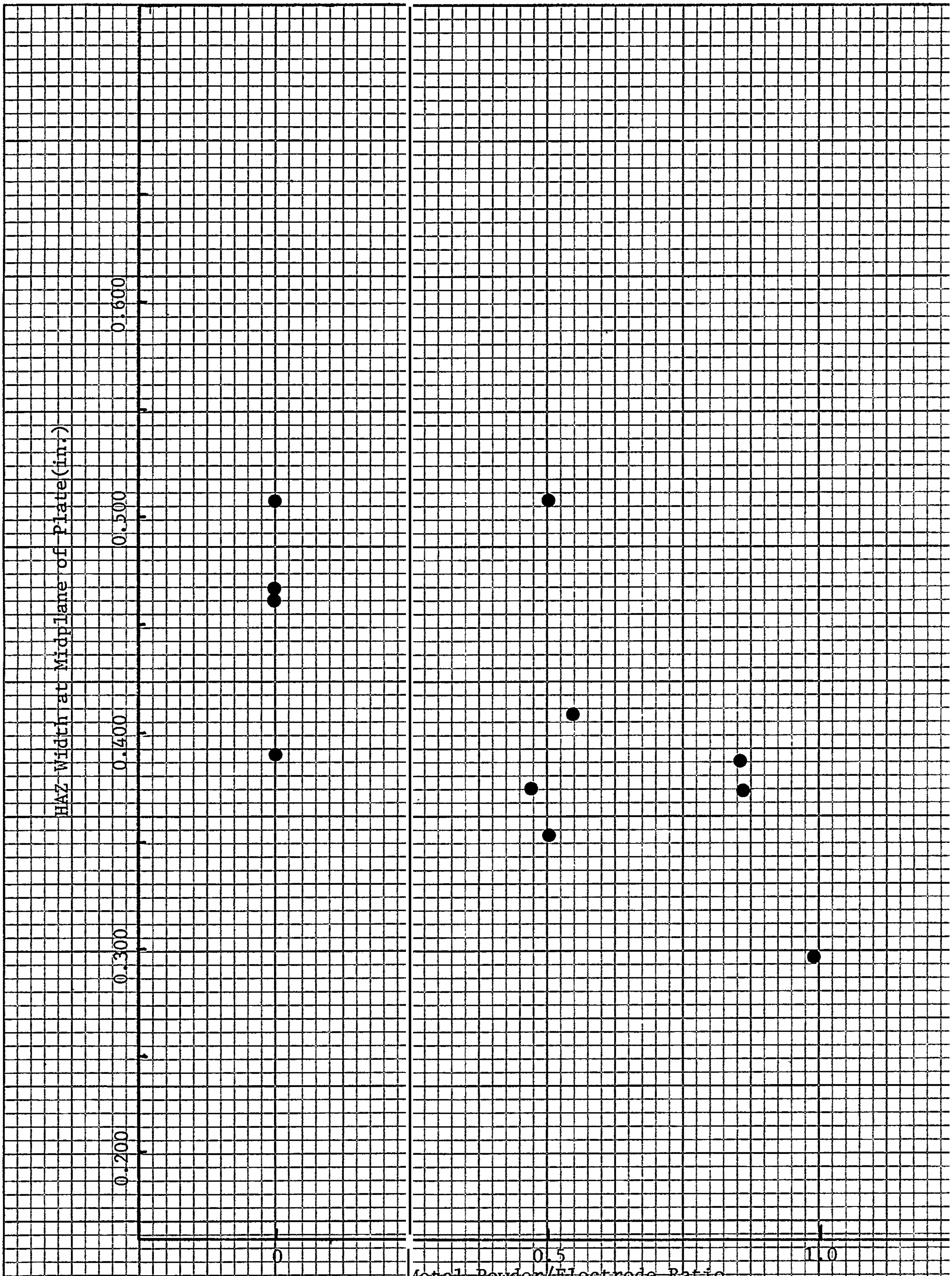


Figure 36 HAZ Width of Electroslag Weldments

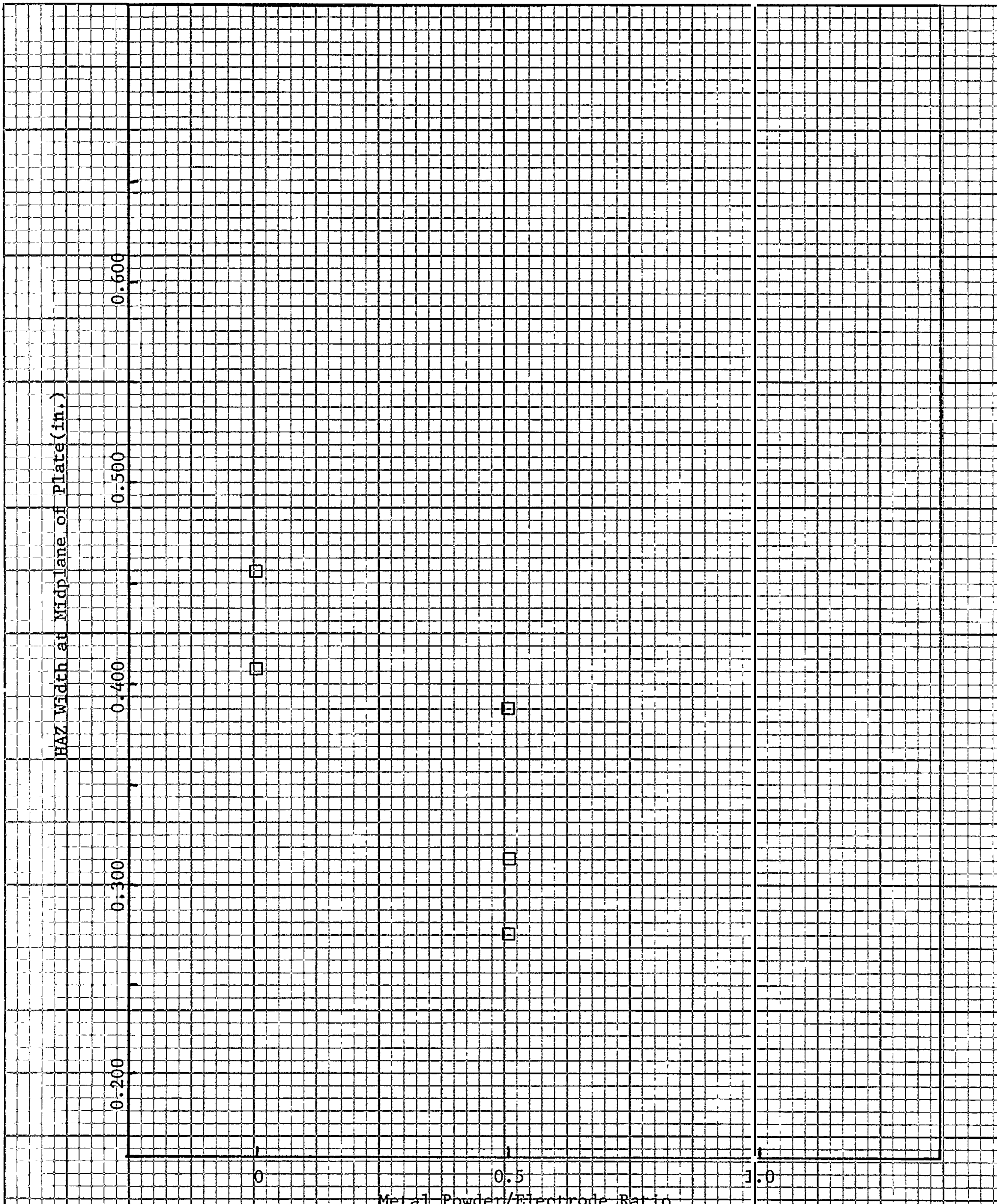


Figure 37. HAZ Width of Electrogas Weldments